

Measurement of the $t\bar{t}$ Production Cross Section in 2 fb^{-1} of $p\bar{p}$ Collisions at $\sqrt{s} = 1.96\text{ TeV}$ Using Lepton Plus Jets Events with Soft Muon b-Tagging

T. Aaltonen,²⁴ J. Adelman,¹⁴ T. Akimoto,⁵⁶ B. Álvarez González^{s, 12} S. Amerio^{y, 44}
D. Amidei,³⁵ A. Anastassov,³⁹ A. Annovi,²⁰ J. Antos,¹⁵ G. Apollinari,¹⁸ A. Apresyan,⁴⁹
T. Arisawa,⁵⁸ A. Artikov,¹⁶ W. Ashmanskas,¹⁸ A. Attal,⁴ A. Aurisano,⁵⁴ F. Azfar,⁴³
P. Azzurri^{z, 47} W. Badgett,¹⁸ A. Barbaro-Galtieri,²⁹ V.E. Barnes,⁴⁹ B.A. Barnett,²⁶
V. Bartsch,³¹ G. Bauer,³³ P.-H. Beauchemin,³⁴ F. Bedeschi,⁴⁷ D. Beecher,³¹ S. Behari,²⁶
G. Bellettini^{z, 47} J. Bellinger,⁶⁰ D. Benjamin,¹⁷ A. Beretvas,¹⁸ J. Beringer,²⁹ A. Bhatti,⁵¹
M. Binkley,¹⁸ D. Bisello^{y, 44} I. Bizjak^{ee, 31} R.E. Blair,² C. Blocker,⁷ B. Blumenfeld,²⁶
A. Bocci,¹⁷ A. Bodek,⁵⁰ V. Boisvert,⁵⁰ G. Bolla,⁴⁹ D. Bortoletto,⁴⁹ J. Boudreau,⁴⁸
A. Boveia,¹¹ B. Brau^{a, 11} A. Bridgeman,²⁵ L. Brigliadori,⁴⁴ C. Bromberg,³⁶ E. Brubaker,¹⁴
J. Budagov,¹⁶ H.S. Budd,⁵⁰ S. Budd,²⁵ S. Burke,¹⁸ K. Burkett,¹⁸ G. Busetto^{y, 44}
P. Bussey,²² A. Buzatu,³⁴ K. L. Byrum,² S. Cabrera^{u, 17} C. Calancha,³² M. Campanelli,³⁶
M. Campbell,³⁵ F. Canelli^{14, 18} A. Canepa,⁴⁶ B. Carls,²⁵ D. Carlsmith,⁶⁰ R. Carosi,⁴⁷
S. Carrillo^{n, 19} S. Carron,³⁴ B. Casal,¹² M. Casarsa,¹⁸ A. Castro^{x, 6} P. Catastini^{aa, 47}
D. Cauz^{dd, 55} V. Cavaliere^{aa, 47} M. Cavalli-Sforza,⁴ A. Cerri,²⁹ L. Cerrito^{o, 31} S.H. Chang,²⁸
Y.C. Chen,¹ M. Chertok,⁸ G. Chiarelli,⁴⁷ G. Chlachidze,¹⁸ F. Chlebana,¹⁸ K. Cho,²⁸
D. Chokheli,¹⁶ J.P. Chou,²³ G. Choudalakis,³³ S.H. Chuang,⁵³ K. Chung,¹³ W.H. Chung,⁶⁰
Y.S. Chung,⁵⁰ T. Chwalek,²⁷ C.I. Ciobanu,⁴⁵ M.A. Ciocci^{aa, 47} A. Clark,²¹ D. Clark,⁷
G. Compostella,⁴⁴ M.E. Convery,¹⁸ J. Conway,⁸ M. Cordelli,²⁰ G. Cortiana^{y, 44} C.A. Cox,⁸
D.J. Cox,⁸ F. Crescioli^{z, 47} C. Cuenca Almenar^{u, 8} J. Cuevas^{s, 12} R. Culbertson,¹⁸
J.C. Cully,³⁵ D. Dagenhart,¹⁸ M. Datta,¹⁸ T. Davies,²² P. de Barbaro,⁵⁰ S. De Cecco,⁵²
A. Deisher,²⁹ G. De Lorenzo,⁴ M. Dell'Orso^{z, 47} C. Deluca,⁴ L. Demortier,⁵¹ J. Deng,¹⁷
M. Deninno,⁶ P.F. Derwent,¹⁸ G.P. di Giovanni,⁴⁵ C. Dionisi^{cc, 52} B. Di Ruzza^{dd, 55}
J.R. Dittmann,⁵ M. D'Onofrio,⁴ S. Donati^{z, 47} P. Dong,⁹ J. Donini,⁴⁴ T. Dorigo,⁴⁴

S. Dube,⁵³ J. Efron,⁴⁰ A. Elagin,⁵⁴ R. Erbacher,⁸ D. Errede,²⁵ S. Errede,²⁵ R. Eusebi,¹⁸
 H.C. Fang,²⁹ S. Farrington,⁴³ W.T. Fedorko,¹⁴ R.G. Feild,⁶¹ M. Feindt,²⁷ J.P. Fernandez,³²
 C. Ferrazza^{bb,47} R. Field,¹⁹ G. Flanagan,⁴⁹ R. Forrest,⁸ M.J. Frank,⁵ M. Franklin,²³
 J.C. Freeman,¹⁸ I. Furic,¹⁹ M. Gallinaro,⁵² J. Galyardt,¹³ F. Garberson,¹¹ J.E. Garcia,²¹
 A.F. Garfinkel,⁴⁹ K. Genser,¹⁸ H. Gerberich,²⁵ D. Gerdes,³⁵ A. Gessler,²⁷ S. Giagu^{cc,52}
 V. Giakoumopoulou,³ P. Giannetti,⁴⁷ K. Gibson,⁴⁸ J.L. Gimmell,⁵⁰ C.M. Ginsburg,¹⁸
 N. Giokaris,³ M. Giordani^{dd,55} P. Giromini,²⁰ M. Giunta^{z,47} G. Giurgiu,²⁶ V. Glagolev,¹⁶
 D. Glenzinski,¹⁸ M. Gold,³⁸ N. Goldschmidt,¹⁹ A. Golossanov,¹⁸ G. Gomez,¹²
 G. Gomez-Ceballos,³³ M. Goncharov,³³ O. González,³² I. Gorelov,³⁸ A.T. Goshaw,¹⁷
 K. Goulianos,⁵¹ A. Gresele^{y,44} S. Grinstein,²³ C. Grosso-Pilcher,¹⁴ R.C. Group,¹⁸
 U. Grundler,²⁵ J. Guimaraes da Costa,²³ Z. Gunay-Unalan,³⁶ C. Haber,²⁹ K. Hahn,³³
 S.R. Hahn,¹⁸ E. Halkiadakis,⁵³ B.-Y. Han,⁵⁰ J.Y. Han,⁵⁰ F. Happacher,²⁰ K. Hara,⁵⁶
 D. Hare,⁵³ M. Hare,⁵⁷ S. Harper,⁴³ R.F. Harr,⁵⁹ R.M. Harris,¹⁸ M. Hartz,⁴⁸
 K. Hatakeyama,⁵¹ C. Hays,⁴³ M. Heck,²⁷ A. Heijboer,⁴⁶ J. Heinrich,⁴⁶ C. Henderson,³³
 M. Herndon,⁶⁰ J. Heuser,²⁷ S. Hewamanage,⁵ D. Hidas,¹⁷ C.S. Hill^{c,11} D. Hirschbuehl,²⁷
 A. Hocker,¹⁸ S. Hou,¹ M. Houlden,³⁰ S.-C. Hsu,²⁹ B.T. Huffman,⁴³ R.E. Hughes,⁴⁰
 U. Husemann,⁶¹ M. Hussein,³⁶ J. Huston,³⁶ J. Incandela,¹¹ G. Introzzi,⁴⁷ M. Iori^{cc,52}
 A. Ivanov,⁸ E. James,¹⁸ D. Jang,¹³ B. Jayatilaka,¹⁷ E.J. Jeon,²⁸ M.K. Jha,⁶ S. Jindariani,¹⁸
 W. Johnson,⁸ M. Jones,⁴⁹ K.K. Joo,²⁸ S.Y. Jun,¹³ J.E. Jung,²⁸ T.R. Junk,¹⁸ T. Kamon,⁵⁴
 D. Kar,¹⁹ P.E. Karchin,⁵⁹ Y. Kato^{l,42} R. Kephart,¹⁸ J. Keung,⁴⁶ V. Khotilovich,⁵⁴
 B. Kilminster,¹⁸ D.H. Kim,²⁸ H.S. Kim,²⁸ H.W. Kim,²⁸ J.E. Kim,²⁸ M.J. Kim,²⁰
 S.B. Kim,²⁸ S.H. Kim,⁵⁶ Y.K. Kim,¹⁴ N. Kimura,⁵⁶ L. Kirsch,⁷ S. Klimenko,¹⁹
 B. Knuteson,³³ B.R. Ko,¹⁷ K. Kondo,⁵⁸ D.J. Kong,²⁸ J. Konigsberg,¹⁹ A. Korytov,¹⁹
 A.V. Kotwal,¹⁷ M. Kreps,²⁷ J. Kroll,⁴⁶ D. Krop,¹⁴ N. Krumnack,⁵ M. Kruse,¹⁷
 V. Krutelyov,¹¹ T. Kubo,⁵⁶ T. Kuhr,²⁷ N.P. Kulkarni,⁵⁹ M. Kurata,⁵⁶ S. Kwang,¹⁴
 A.T. Laasanen,⁴⁹ S. Lami,⁴⁷ S. Lammel,¹⁸ M. Lancaster,³¹ R.L. Lander,⁸ K. Lannon^{r,40}
 A. Lath,⁵³ G. Latino^{aa,47} I. Lazzizzera^{y,44} T. LeCompte,² E. Lee,⁵⁴ H.S. Lee,¹⁴ S.W. Lee^{t,54}
 S. Leone,⁴⁷ J.D. Lewis,¹⁸ C.-S. Lin,²⁹ J. Linacre,⁴³ M. Lindgren,¹⁸ E. Lipeles,⁴⁶
 T.M. Liss,²⁵ A. Lister,⁸ D.O. Litvintsev,¹⁸ C. Liu,⁴⁸ T. Liu,¹⁸ N.S. Lockyer,⁴⁶
 A. Loginov,⁶¹ M. Loreti^{y,44} L. Lovas,¹⁵ D. Lucchesi^{y,44} C. Luci^{cc,52} J. Lueck,²⁷ P. Lujan,²⁹

P. Lukens,¹⁸ G. Lungu,⁵¹ L. Lyons,⁴³ J. Lys,²⁹ R. Lysak,¹⁵ D. MacQueen,³⁴ R. Madrak,¹⁸
 K. Maeshima,¹⁸ K. Makhoul,³³ T. Maki,²⁴ P. Maksimovic,²⁶ S. Malde,⁴³ S. Malik,³¹
 G. Manca^{e,30} A. Manousakis-Katsikakis,³ F. Margaroli,⁴⁹ C. Marino,²⁷ C.P. Marino,²⁵
 A. Martin,⁶¹ V. Martin^{k,22} M. Martínez,⁴ R. Martínez-Ballarín,³² T. Maruyama,⁵⁶
 P. Mastrandrea,⁵² T. Masubuchi,⁵⁶ M. Mathis,²⁶ M.E. Mattson,⁵⁹ P. Mazzanti,⁶
 K.S. McFarland,⁵⁰ P. McIntyre,⁵⁴ R. McNulty^{j,30} A. Mehta,³⁰ P. Mehtala,²⁴ A. Menzione,⁴⁷
 P. Merkel,⁴⁹ C. Mesropian,⁵¹ T. Miao,¹⁸ N. Miladinovic,⁷ R. Miller,³⁶ C. Mills,²³
 M. Milnik,²⁷ A. Mitra,¹ G. Mitselmakher,¹⁹ H. Miyake,⁵⁶ N. Moggi,⁶ C.S. Moon,²⁸
 R. Moore,¹⁸ M.J. Morello^{z,47} J. Morlock,²⁷ P. Movilla Fernandez,¹⁸ J. Mülmenstädt,²⁹
 A. Mukherjee,¹⁸ Th. Muller,²⁷ R. Mumford,²⁶ P. Murat,¹⁸ M. Mussini^{x,6} J. Nachtman,¹⁸
 Y. Nagai,⁵⁶ A. Nagano,⁵⁶ J. Naganoma,⁵⁶ K. Nakamura,⁵⁶ I. Nakano,⁴¹ A. Napier,⁵⁷
 V. Necula,¹⁷ J. Nett,⁶⁰ C. Neu^{v,46} M.S. Neubauer,²⁵ S. Neubauer,²⁷ J. Nielsen^{g,29}
 L. Nodulman,² M. Norman,¹⁰ O. Norniella,²⁵ E. Nurse,³¹ L. Oakes,⁴³ S.H. Oh,¹⁷ Y.D. Oh,²⁸
 I. Oksuzian,¹⁹ T. Okusawa,⁴² R. Orava,²⁴ K. Osterberg,²⁴ S. Pagan Griso^{y,44} E. Palencia,¹⁸
 V. Papadimitriou,¹⁸ A. Papaikonomou,²⁷ A.A. Paramonov,¹⁴ B. Parks,⁴⁰ S. Pashapour,³⁴
 J. Patrick,¹⁸ G. Pauletta^{dd,55} M. Paulini,¹³ C. Paus,³³ T. Peiffer,²⁷ D.E. Pellett,⁸
 A. Penzo,⁵⁵ T.J. Phillips,¹⁷ G. Piacentino,⁴⁷ E. Pianori,⁴⁶ L. Pinera,¹⁹ K. Pitts,²⁵
 C. Plager,⁹ L. Pondrom,⁶⁰ O. Poukhov*,¹⁶ N. Pounder,⁴³ F. Prakoshyn,¹⁶ A. Pronko,¹⁸
 J. Proudfoot,² F. Ptohos^{i,18} E. Pueschel,¹³ G. Punzi^{z,47} J. Pursley,⁶⁰ J. Rademacker^{c,43}
 A. Rahaman,⁴⁸ V. Ramakrishnan,⁶⁰ N. Ranjan,⁴⁹ I. Redondo,³² P. Renton,⁴³ M. Renz,²⁷
 M. Rescigno,⁵² S. Richter,²⁷ F. Rimondi^{x,6} L. Ristori,⁴⁷ A. Robson,²² T. Rodrigo,¹²
 T. Rodriguez,⁴⁶ E. Rogers,²⁵ S. Rolli,⁵⁷ R. Roser,¹⁸ M. Rossi,⁵⁵ R. Rossin,¹¹ P. Roy,³⁴
 A. Ruiz,¹² J. Russ,¹³ V. Rusu,¹⁸ B. Rutherford,¹⁸ H. Saarikko,²⁴ A. Safonov,⁵⁴
 W.K. Sakumoto,⁵⁰ O. Saltó,⁴ L. Santi^{dd,55} S. Sarkar^{cc,52} L. Sartori,⁴⁷ K. Sato,¹⁸
 A. Savoy-Navarro,⁴⁵ P. Schlabach,¹⁸ A. Schmidt,²⁷ E.E. Schmidt,¹⁸ M.A. Schmidt,¹⁴
 M.P. Schmidt*,⁶¹ M. Schmitt,³⁹ T. Schwarz,⁸ L. Scodellaro,¹² A. Scribano^{aa,47} F. Scuri,⁴⁷
 A. Sedov,⁴⁹ S. Seidel,³⁸ Y. Seiya,⁴² A. Semenov,¹⁶ L. Sexton-Kennedy,¹⁸ F. Sforza,⁴⁷
 A. Sfyrila,²⁵ S.Z. Shalhout,⁵⁹ T. Shears,³⁰ P.F. Shepard,⁴⁸ M. Shimojima^{q,56} S. Shiraishi,¹⁴
 M. Shochet,¹⁴ Y. Shon,⁶⁰ I. Shreyber,³⁷ A. Sidoti,⁴⁷ P. Sinervo,³⁴ A. Sisakyan,¹⁶

* Deceased

A.J. Slaughter,¹⁸ J. Slaunwhite,⁴⁰ K. Sliwa,⁵⁷ J.R. Smith,⁸ F.D. Snider,¹⁸ R. Snihur,³⁴
A. Soha,⁸ S. Somalwar,⁵³ V. Sorin,³⁶ J. Spalding,¹⁸ T. Spreitzer,³⁴ P. Squillacioti^{aa,47}
M. Stanitzki,⁶¹ R. St. Denis,²² B. Stelzer,³⁴ O. Stelzer-Chilton,³⁴ D. Stentz,³⁹
J. Strologas,³⁸ G.L. Strycker,³⁵ D. Stuart,¹¹ J.S. Suh,²⁸ A. Sukhanov,¹⁹ I. Suslov,¹⁶
T. Suzuki,⁵⁶ A. Taffard^{f,25} R. Takashima,⁴¹ Y. Takeuchi,⁵⁶ R. Tanaka,⁴¹ M. Tecchio,³⁵
P.K. Teng,¹ K. Terashi,⁵¹ J. Thom^{h,18} A.S. Thompson,²² G.A. Thompson,²⁵ E. Thomson,⁴⁶
P. Tipton,⁶¹ P. Ttito-Guzmán,³² S. Tkaczyk,¹⁸ D. Toback,⁵⁴ S. Tokar,¹⁵ K. Tollefson,³⁶
T. Tomura,⁵⁶ D. Tonelli,¹⁸ S. Torre,²⁰ D. Torretta,¹⁸ P. Totaro^{dd,55} S. Tourneur,⁴⁵
M. Trovato,⁴⁷ S.-Y. Tsai,¹ Y. Tu,⁴⁶ N. Turini^{aa,47} F. Ukegawa,⁵⁶ S. Vallecorsa,²¹
N. van Remortel^{b,24} A. Varganov,³⁵ E. Vataga^{bb,47} F. Vázquez^{n,19} G. Velez,¹⁸ C. Vellidis,³
M. Vidal,³² R. Vidal,¹⁸ I. Vila,¹² R. Vilar,¹² T. Vine,³¹ M. Vogel,³⁸ I. Volobouev^{t,29}
G. Volpi^{z,47} P. Wagner,⁴⁶ R.G. Wagner,² R.L. Wagner,¹⁸ W. Wagner^{w,27} J. Wagner-Kuhr,²⁷
T. Wakisaka,⁴² R. Wallny,⁹ S.M. Wang,¹ A. Warburton,³⁴ D. Waters,³¹ M. Weinberger,⁵⁴
J. Weinelt,²⁷ W.C. Wester III,¹⁸ B. Whitehouse,⁵⁷ D. Whiteson^{f,46} A.B. Wicklund,²
E. Wicklund,¹⁸ S. Wilbur,¹⁴ G. Williams,³⁴ H.H. Williams,⁴⁶ P. Wilson,¹⁸ B.L. Winer,⁴⁰
P. Wittich^{h,18} S. Wolbers,¹⁸ C. Wolfe,¹⁴ T. Wright,³⁵ X. Wu,²¹ F. Würthwein,¹⁰ S. Xie,³³
A. Yagil,¹⁰ K. Yamamoto,⁴² J. Yamaoka,¹⁷ U.K. Yang^{p,14} Y.C. Yang,²⁸ W.M. Yao,²⁹
G.P. Yeh,¹⁸ J. Yoh,¹⁸ K. Yorita,⁵⁸ T. Yoshida^{m,42} G.B. Yu,⁵⁰ I. Yu,²⁸ S.S. Yu,¹⁸
J.C. Yun,¹⁸ L. Zanello^{cc,52} A. Zanetti,⁵⁵ X. Zhang,²⁵ Y. Zheng^{d,9} and S. Zucchelli^{x,6}

(CDF Collaboration[†])

[†] With visitors from ^aUniversity of Massachusetts Amherst, Amherst, Massachusetts 01003, ^bUniversiteit Antwerpen, B-2610 Antwerp, Belgium, ^cUniversity of Bristol, Bristol BS8 1TL, United Kingdom, ^dChinese Academy of Sciences, Beijing 100864, China, ^eIstituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, ^fUniversity of California Irvine, Irvine, CA 92697, ^gUniversity of California Santa Cruz, Santa Cruz, CA 95064, ^hCornell University, Ithaca, NY 14853, ⁱUniversity of Cyprus, Nicosia CY-1678, Cyprus, ^jUniversity College Dublin, Dublin 4, Ireland, ^kUniversity of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, ^lUniversity of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017 ^mKinki University, Higashi-Osaka City, Japan 577-8502 ⁿUniversidad Iberoamericana, Mexico D.F., Mexico, ^oQueen Mary, University of London, London, E1 4NS, England, ^pUniversity of Manchester, Manchester M13 9PL, England, ^qNagasaki Institute of Applied Science, Nagasaki, Japan, ^rUniversity of Notre Dame, Notre Dame, IN 46556, ^sUniversity de Oviedo, E-33007 Oviedo, Spain, ^tTexas Tech University, Lubbock, TX 79609, ^uIFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain, ^vUniversity of Virginia, Charlottesville, VA 22904, ^wBergische Universität Wuppertal, 42097 Wuppertal, Germany, ^{ee}On leave from J. Stefan Institute, Ljubljana, Slovenia,

- ¹*Institute of Physics, Academia Sinica,
Taipei, Taiwan 11529, Republic of China*
- ²*Argonne National Laboratory, Argonne, Illinois 60439*
- ³*University of Athens, 157 71 Athens, Greece*
- ⁴*Institut de Fisica d'Altes Energies,
Universitat Autònoma de Barcelona,
E-08193, Bellaterra (Barcelona), Spain*
- ⁵*Baylor University, Waco, Texas 76798*
- ⁶*Istituto Nazionale di Fisica Nucleare Bologna,*
^x*University of Bologna, I-40127 Bologna, Italy*
- ⁷*Brandeis University, Waltham, Massachusetts 02254*
- ⁸*University of California, Davis, Davis, California 95616*
- ⁹*University of California, Los Angeles, Los Angeles, California 90024*
- ¹⁰*University of California, San Diego, La Jolla, California 92093*
- ¹¹*University of California, Santa Barbara, Santa Barbara, California 93106*
- ¹²*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
- ¹³*Carnegie Mellon University, Pittsburgh, PA 15213*
- ¹⁴*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
- ¹⁵*Comenius University, 842 48 Bratislava,
Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
- ¹⁶*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
- ¹⁷*Duke University, Durham, North Carolina 27708*
- ¹⁸*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
- ¹⁹*University of Florida, Gainesville, Florida 32611*
- ²⁰*Laboratori Nazionali di Frascati, Istituto Nazionale
di Fisica Nucleare, I-00044 Frascati, Italy*
- ²¹*University of Geneva, CH-1211 Geneva 4, Switzerland*
- ²²*Glasgow University, Glasgow G12 8QQ, United Kingdom*
- ²³*Harvard University, Cambridge, Massachusetts 02138*
- ²⁴*Division of High Energy Physics, Department of Physics,
University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
- ²⁵*University of Illinois, Urbana, Illinois 61801*

- ²⁶*The Johns Hopkins University, Baltimore, Maryland 21218*
- ²⁷*Institut für Experimentelle Kernphysik,
Universität Karlsruhe, 76128 Karlsruhe, Germany*
- ²⁸*Center for High Energy Physics: Kyungpook National University,
Daegu 702-701, Korea; Seoul National University, Seoul 151-742,
Korea; Sungkyunkwan University, Suwon 440-746,
Korea; Korea Institute of Science and Technology Information, Daejeon,
305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea*
- ²⁹*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
- ³⁰*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- ³¹*University College London, London WC1E 6BT, United Kingdom*
- ³²*Centro de Investigaciones Energeticas
Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
- ³³*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
- ³⁴*Institute of Particle Physics: McGill University, Montréal,
Québec, Canada H3A 2T8; Simon Fraser University, Burnaby,
British Columbia, Canada V5A 1S6; University of Toronto,
Toronto, Ontario, Canada M5S 1A7; and TRIUMF,
Vancouver, British Columbia, Canada V6T 2A3*
- ³⁵*University of Michigan, Ann Arbor, Michigan 48109*
- ³⁶*Michigan State University, East Lansing, Michigan 48824*
- ³⁷*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
- ³⁸*University of New Mexico, Albuquerque, New Mexico 87131*
- ³⁹*Northwestern University, Evanston, Illinois 60208*
- ⁴⁰*The Ohio State University, Columbus, Ohio 43210*
- ⁴¹*Okayama University, Okayama 700-8530, Japan*
- ⁴²*Osaka City University, Osaka 588, Japan*
- ⁴³*University of Oxford, Oxford OX1 3RH, United Kingdom*
- ⁴⁴*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento,
University of Padova, I-35131 Padova, Italy*
- ⁴⁵*LPNHE, Universite Pierre et Marie
Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*

⁴⁶*University of Pennsylvania, Philadelphia, Pennsylvania 19104*

⁴⁷*Istituto Nazionale di Fisica Nucleare Pisa, ^zUniversity of Pisa,*

^{aa}*University of Siena and ^{bb}Scuola Normale Superiore, I-56127 Pisa, Italy*

⁴⁸*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*

⁴⁹*Purdue University, West Lafayette, Indiana 47907*

⁵⁰*University of Rochester, Rochester, New York 14627*

⁵¹*The Rockefeller University, New York, New York 10021*

⁵²*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,*

^{cc}*Sapienza Università di Roma, I-00185 Roma, Italy*

⁵³*Rutgers University, Piscataway, New Jersey 08855*

⁵⁴*Texas A&M University, College Station, Texas 77843*

⁵⁵*Istituto Nazionale di Fisica Nucleare Trieste/Udine,
I-34100 Trieste, ^{dd}University of Trieste/Udine, I-33100 Udine, Italy*

⁵⁶*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*

⁵⁷*Tufts University, Medford, Massachusetts 02155*

⁵⁸*Waseda University, Tokyo 169, Japan*

⁵⁹*Wayne State University, Detroit, Michigan 48201*

⁶⁰*University of Wisconsin, Madison, Wisconsin 53706*

⁶¹*Yale University, New Haven, Connecticut 06520*

(Dated: January 26, 2009)

Abstract

We present a measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using events containing a high transverse momentum electron or muon, three or more jets, and missing transverse energy. Events consistent with $t\bar{t}$ decay are found by identifying jets containing candidate heavy-flavor semileptonic decays to muons. The measurement uses a CDF Run II data sample corresponding to 2 fb^{-1} of integrated luminosity. Based on 248 candidate events with three or more jets and an expected background of 79.5 ± 5.3 events, we measure a production cross section of $9.1 \pm 1.6\text{ pb}$.

PACS numbers: 13.85Ni, 13.85Qk, 14.65Ha

I. INTRODUCTION

Top quark pair production in hadronic collisions in the standard model proceeds via either quark-antiquark annihilation or through gluon-gluon fusion. At the Fermilab Tevatron collider, with a center-of-mass energy of 1.96 TeV, the production is expected to be dominated by quark-antiquark annihilation. For a top mass of 175 GeV/ c^2 the theoretical cross section is calculated to be 6.6 ± 0.6 pb [1] and decreases by approximately 0.2 pb for each 1 GeV/ c^2 increase in the top mass over the range $170 \text{ GeV}/c^2 < M_{top} < 190 \text{ GeV}/c^2$.

Measurements of the cross section for top quark pair production provide a test of the expected QCD production mechanism as well as of the standard model decay into a W -boson and a bottom quark, $t \rightarrow Wb$. Non-standard model production mechanisms could enhance the measured cross section, and non-standard model decays could suppress the measured value, which assumes a branching fraction of $t \rightarrow Wb$ of 100%.

In this paper we describe a measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF II detector at the Fermilab Tevatron. The measurement assumes the standard model decay $t \rightarrow Wb$ of the top quark, providing a final state from $t\bar{t}$ production that includes two W bosons and two bottom quarks. We select events where one of the W bosons decays to an electron or muon which has large momentum transverse to the beam direction (P_T) plus a neutrino. The neutrino is undetected and results in an imbalance in transverse momentum. This imbalance is labeled “missing E_T ” (\cancel{E}_T) because it is reconstructed based on the flow of energy in the calorimeter [2]. The other W boson in the event decays hadronically to a pair of quarks. The two quarks from the W boson, and the two b quarks from the top decays, hadronize and are observed as jets of charged and neutral particles. We take advantage of the semileptonic decay of b -hadrons to muons to identify final-state jets that result from hadronization of the bottom quarks expected in the top decay. This “soft-lepton tagging” with muons, or SLT μ , is effective in reducing the background to the $t\bar{t}$ signal from W plus multijet production. This technique is complementary to measurements that take advantage of the long lifetime of b -hadrons to identify jets from bottom quark hadronization through the presence of a decay vertex displaced from the primary interaction [3].

This measurement is an update of the measurement described in [4], which was made with approximately one tenth of the integrated luminosity used here. Full details of this

analysis are presented in [5]. In addition to the larger dataset, we report here on a new method for evaluating the background from “mistags”, i.e. those $SLT_{\mu}s$ that do not arise from semi-leptonic decays of heavy-flavor (HF) quarks. This is described in Section VI.

II. THE CDF DETECTOR

The CDF II detector is described in detail in [6]. We describe briefly here those elements of the detector that are central to this analysis. CDF II is a nearly azimuthally and forward-backward symmetric detector designed to study $p\bar{p}$ interactions at the Fermilab Tevatron. It consists of a magnetic spectrometer surrounded by calorimeters and muon chambers. An elevation view of the CDF II detector is shown in Fig. 1.

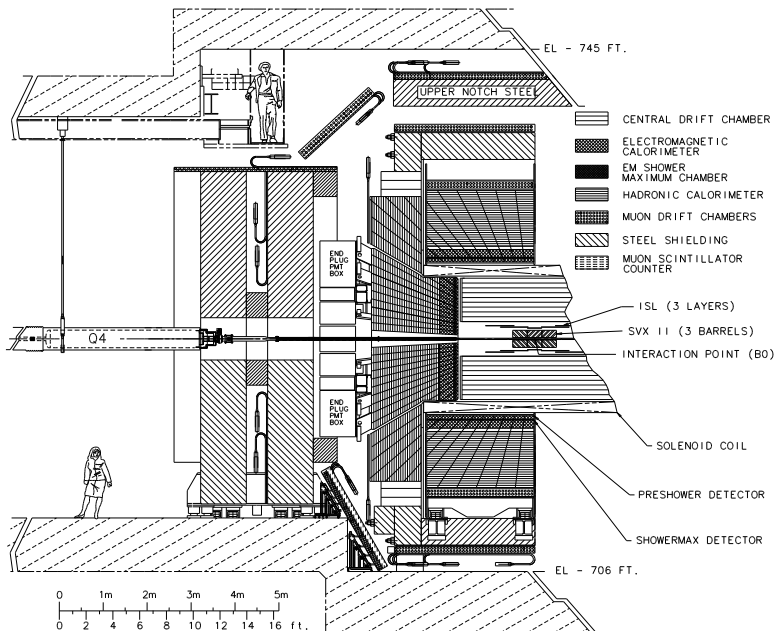


FIG. 1: Elevation view of the CDF II detector.

Charged particles are tracked inside a 1.4 T solenoidal magnetic field by an 8-layer silicon strip detector, covering radii from 1.5 cm to 28 cm, followed by the central outer tracker (COT), an open-cell drift chamber that provides up to 96 measurements of charged particle position over the radial region from 40 cm to 137 cm. The 96 COT measurements are arranged in 8 “superlayers” of 12 sense wires each, that alternate between axial and 2° stereo orientations. The silicon detector tracks charged particles with high efficiency for $|\eta| < 2.0$, and the COT for $|\eta| < 1.0$ [2].

Surrounding the tracking system, and outside the magnet coil, are the electromagnetic and hadronic calorimeters, used to measure charged and neutral particle energies. The electromagnetic calorimeter is a lead-scintillator sandwich and the hadronic calorimeter is an iron-scintillator sandwich. Both calorimeters are segmented in azimuth and polar angle to provide directional information for the energy deposition. The segmentation varies with position on the detector and is 15° in azimuth by 0.1 units of η in the central region ($|\eta| < 1.1$). Segmentation in the plug region ($1.1 < |\eta| < 3.6$) is 7.5° ($|\eta| < 2.1$) or 15° ($|\eta| > 2.1$) in azimuth and ranges from 0.1 to 0.64 units of η (corresponding to a nearly constant 2.7° change in polar angle). The electromagnetic calorimeters are instrumented with proportional and scintillating strip detectors that measure the transverse profile of electromagnetic showers at a depth corresponding to the shower maximum.

Behind the central calorimeter are four layers of central muon drift chambers covering $|\eta| < 0.6$ (CMU). The calorimeter provides approximately one meter of steel shielding. Behind an additional 60 cm of steel in the central region sit an additional four layers of muon drift chambers (CMP) arranged in a box-shaped layout around the central detector. Central muon extension (CMX) chambers, which are arrayed in a conical geometry, provide muon detection for the region $0.6 < |\eta| < 1.0$ with between four and six layers of drift chamber, depending on zenith angle. The CMX chambers covering from 225° to 315° in azimuth are known as the ‘miniskirt’ while those covering from 75° to 105° in azimuth are known as the ‘keystone’. The remainder of the CMX chambers are referred to as the ‘arches’. The muon chambers measure the coordinate of hits in the drift direction, x , via a drift time measurement and a calibrated drift velocity, and for CMU and CMX, the longitudinal coordinate, z . The longitudinal coordinate is measured in CMU by comparing the pulse heights, encoded in time-over-threshold, of pulses at opposite ends of the sense wire. In CMX, the conical geometry provides a small stereo angle from which the z coordinate of track segments can be measured. Reconstructed track segments in CMU and CMP have a maximum of 4 hits, and in CMX a maximum of 6 hits.

III. DATA SAMPLE AND EVENT SELECTION

This analysis is based on an integrated luminosity of $2034 \pm 120 \text{ pb}^{-1}$ [7] (1993 pb^{-1} with the CMX detector operational) collected with the CDF II detector between March 2002 and

May 2007.

A. Kinematic Selection

The triggering and offline event selection used in this analysis are nearly identical to that used in the previous analysis described in [4]. For completeness we reproduce the basic trigger and selection criteria here and highlight the few differences.

CDF II employs a three level trigger system, the first two consisting of special purpose hardware and the third consisting of a farm of commodity computers. Triggers for this analysis are based on selecting high transverse momentum electrons and muons. The electron sample is triggered as follows: At the first trigger level, events are selected by requiring a track with $P_T > 8$ GeV/c matched to an electromagnetic calorimeter tower with $E_T > 8$ GeV and little energy in the hadronic calorimeter behind it. At the second trigger level, calorimeter energy clusters are assembled, and the track found at the first level must be matched to an electromagnetic cluster with $E_T > 16$ GeV. At the third level, offline reconstruction is performed and an electron candidate with $E_T > 18$ GeV is required. The muon sample trigger begins at the first trigger level with a track with $P_T > 4$ GeV/c matched to hits in the CMU and CMP chambers or a track with $P_T > 8$ GeV/c matched to hits in the CMX chambers. At the second level a track with $P_T > 8$ GeV/c is required in the event for all but the first few percent of the integrated luminosity, for which triggers at the first level were fed directly to the third level trigger. At the third trigger level a reconstructed track with $P_T > 18$ GeV/c is required to be matched to the muon chamber hits.

From the inclusive lepton dataset produced by the electron and muon triggers described above, we select offline an inclusive W plus jets candidate sample by requiring a reconstructed isolated electron with $E_T > 20$ GeV or muon with $P_T > 20$ GeV/c, $E_T > 30$ GeV and at least 1 jet with $E_T > 20$ GeV and $|\eta| < 2.0$. We define an isolation parameter, I , as the calorimeter energy in a cone of $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ around the lepton (not including the lepton energy itself) divided by the E_T (P_T) of the lepton. We select isolated electrons (muons) by requiring $I < 0.1$. Electrons and muons satisfying these criteria are called the “primary lepton”. Jets are identified using a fixed-cone algorithm with a cone size of $\Delta R = 0.4$ and are constrained to originate at the $p\bar{p}$ collision vertex. Their energies are corrected to account for detector response variations in η , drifts in calorimeter gain,

nonlinearity of calorimeter energy response, multiple interactions in an event and for energy loss in un-instrumented regions of the detector. These corrections bring the jet energies, on average, back to the sum P_T of the particles in the jet cone, but not all the way back to the parton energy. This is slightly different from the previous analysis [4] where the correction was done only for response variations in η , gain drifts and multiple interactions. The jet counting threshold in that analysis was $E_T > 15$ GeV, which corresponds roughly to the $E_T > 20$ GeV used here with the additional corrections. The missing transverse energy is corrected to account for the shifts in jet energies due to the jet corrections above, and the \cancel{E}_T threshold has been raised from 20 GeV in the previous analysis to 30 GeV here, consistent with the change in jet corrections. Z boson candidate events are rejected by removing events in which a second, same flavor, opposite sign isolated lepton, together with the primary lepton, makes an invariant mass between 76 GeV/ c^2 and 106 GeV/ c^2 . The acceptance of these selection criteria for $t\bar{t}$ events is discussed in Section V below.

The $t\bar{t}$ signal region consists of W candidate events with 3 or more jets, while the $W+1$ and $W+2$ jet events provide a control sample with little signal contamination.

The dataset selected above is dominated by QCD production of W bosons with multiple jets. As a first stage of background reduction, we define a total event transverse energy, H_T , as the scalar sum of the electron E_T or muon P_T , \cancel{E}_T and jet E_T for jets with $E_T > 8$ GeV and $|\eta| < 2.4$. Figure 2 shows a comparison between the H_T distributions for simulated $t\bar{t}$ and W +jets events with at least 3 jets. For 3 or more jet events, we require $H_T > 200$ GeV. This requirement rejects approximately 30% of the background while retaining approximately 99% of the $t\bar{t}$ signal. No H_T requirement is made for the control region of 1- and 2-jet events.

B. Muon Tagging

Even after the H_T requirement is imposed, the expected signal to background ratio in $W + \geq 3$ jet events is about 1:7. To further improve the signal to background ratio, events with one or more b -jets are identified by searching inside jets for semileptonic decays of b -hadrons into muons. The algorithm for identifying such candidate b -jets is known as “soft lepton tagging” or “SLT μ ” and a jet with a candidate semileptonic b decay to a muon is a “tagged” jet. The SLT μ algorithm is described in detail in Reference [4]. We review here

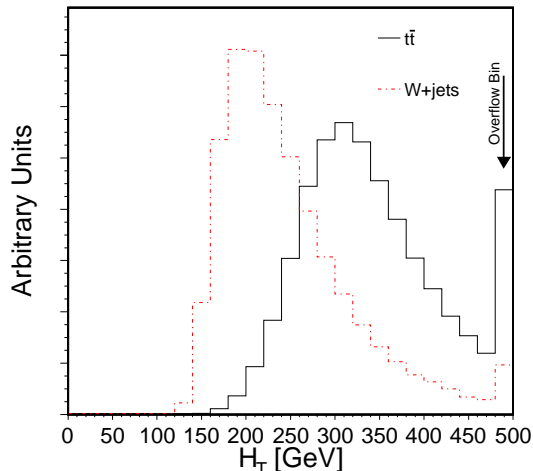


FIG. 2: The distribution of H_T for simulated $t\bar{t}$ and $W + \text{jets}$ events with at least three jets.

only its basic features.

Muon identification at CDF relies on the presence of a track segment (“stub”) in the muon chambers, matched to a track in the central tracking system. The soft muon tagger is based on a χ^2 function that uses all available information about the match between the extrapolated COT track and the muon stub to require that the deviations be consistent with the multiple Coulomb scattering expected for a muon traversing the CDF calorimeter.

The algorithm begins by selecting “taggable” tracks. A track is declared taggable if it contains at least 3 axial and 2 stereo COT superlayers that have at least 5 hits each. To obtain some rejection for decays-in-flight (DIF), the impact parameter, d_0 , of the track with respect to the beamline, is required to be less than 2 mm. The track is further required to originate within 60 cm of the center of the detector along the beam direction. Finally, the track must have a P_T above an approximate range-out threshold of 3.0 GeV/c and extrapolate to within a fiducial volume at the muon chambers that extends $3\sigma_{MS}$ outside of the physical edges of the chambers, where σ_{MS} is the deviation expected from multiple Coulomb scattering at the track P_T .

Matching between the extrapolated COT track and the muon stub is done using the following observables (“matching variables”): The extrapolated position along the muon chamber drift direction (x), the longitudinal coordinate along the chamber wires (z) when such information is available, and the extrapolated slope (ϕ_L). Tracks in the COT are paired

with stubs based on the best match in x , which must be less than 50 cm for a track-stub pair to become a muon candidate. We refer to the difference between the extrapolated and measured positions in x and z as Δx and Δz , respectively, and between the extrapolated and measured slope as $\Delta\phi_L$. The distributions of these variables over an ensemble of events are referred to as the “matching distributions”.

Candidate muons are selected with the SLT μ algorithm by constructing a global χ^2 quantity, L , based on a comparison of the measured matching variables with their expectations. The first step in constructing L is taking a sum, Q , of individual χ^2 variables:

$$Q = \sum_{i=1}^n \frac{(X_i - \mu_i)^2}{\sigma_i^2}, \quad (1)$$

where μ_i and σ_i are, respectively, the expected mean and width of the distribution of the matching variable X_i . The sum is taken over n selected variables as described below. We construct L , by normalizing Q according to

$$L = \frac{(Q - n)}{\sqrt{\text{var}(Q)}}, \quad (2)$$

where the variance, $\text{var}(Q)$, is calculated using the full covariance matrix for the selected variables. The normalization is chosen to make L independent of the number of variables n .

The selected variables are the full set of matching variables, Δx , Δz , $\Delta\phi_L$ in the CMU, CMP and CMX with the following two exceptions: The CMP chambers do not provide a measurement of the longitudinal coordinate z , and matching in ϕ_L is not included for stubs in the muon chambers that have only three hits. Because of their significantly poorer resolution, track segments reconstructed only in the CMU or only in the CMP chambers with only three hits are rejected (if the SLT μ candidate has stubs in both CMU and CMP, then a stub with only three hits is allowed). These two exceptions are a new feature of the algorithm, since the previous publication, that reduce backgrounds from hadronic punch-through with a negligible effect on the efficiency. Note that a muon that traverses both the CMU and the CMP chambers yields two sets of matching measurements in x and ϕ_L and one z matching measurement, and is referred to as a CMUP muon. All available matching variables are used in the calculation of L for a given muon candidate.

As described in Reference [4], the expected means and widths in equation 1 are parameterized as a function of the P_T of the muon using J/ψ and W and Z bosons in the data.

We use the same parametrization described there. The efficiency has been remeasured, from the data, using the full dataset for this analysis.

Using J/ψ events only, we measure the efficiency as a function of the quantity L defined in equation 2 (the efficiency measurement is described in detail in Section V B). The efficiency plateaus at a value of $|L| \leq 3.5$, and we therefore use this requirement to define an SLT μ tag.

Beginning with the W +jets candidate dataset, selected as described in Section III A above, we require that at least one jet in each event has an SLT μ tag. A jet is determined to have an SLT μ tag if a candidate muon with $|L| \leq 3.5$ is found within a cone of $\Delta R < 0.6$ centered on the jet axis. When the primary lepton is a muon, the event is rejected when the SLT μ has opposite charge to the primary muon and together with that muon has an invariant mass between 8 and 11 GeV/ c^2 or between 70 and 110 GeV/ c^2 . This rejects events in which an Υ or Z boson decays to a pair of muons, one of which becomes the primary lepton while the other ends up in a jet and is tagged by the SLT μ algorithm. Whether the primary is an electron or a muon, events where the invariant mass is less than 5 GeV/ c^2 are also removed to prevent sequential double-semileptonic $b \rightarrow c \rightarrow s$ decays (where the primary lepton and the SLT μ tag are from these semileptonic decays, rather than the primary lepton being from the decay of a W boson) from entering the sample, as well as events with a J/ψ decay. We further reject events as candidate radiative Drell-Yan and Z bosons if the tagged jet has an electromagnetic energy fraction above 0.8 and only one track with $P_T > 1.0 \text{ GeV}/c$ within a cone of $\Delta R = 0.4$ about the jet axis.

Three levels of selection are defined in this analysis. Events that pass the kinematic cuts and the dilepton and radiative- Z vetoes, but do not necessarily have an SLT μ -taggable track in them, comprise the “pretag” sample. Pretag events that have an SLT μ -taggable track ($P_T > 3 \text{ GeV}/c$, passing quality cuts, pointing to the muon chambers) within $\Delta R < 0.6$ of a jet with $E_T > 20 \text{ GeV}$ are called taggable events. Finally, the subset of SLT μ -taggable events that have at least one SLT μ -tagged jet are called tagged events.

C. Selected Event Samples

Table I shows the number of pretagged, taggable and tagged events in the electron and muon channels in this dataset as a function of jet multiplicity.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Electrons					
Pretag	79348	13068	1615	660	2275
SLT μ Taggable	43005	10479	1518	648	2166
SLT μ Tagged	519	224	85	64	149
CMUP Muons					
Pretag	38165	6320	719	325	1044
SLT μ Taggable	20162	4921	673	312	985
SLT μ Tagged	224	105	41	34	75
CMX Muons					
Pretag	23503	3672	422	162	584
SLT μ Taggable	12428	2864	396	160	556
SLT μ Tagged	149	55	16	8	24
Electrons+Muons					
Pretag	141016	23060	2756	1147	3903
SLT μ Taggable	75595	18264	2587	1120	3707
SLT μ Tagged	892	384	142	106	248

TABLE I: Summary of event counts for 2 fb^{-1} of CDF Run II data for the event selection described in Sections III A and III B.

IV. MONTE CARLO DATASETS

The detector acceptance of $t\bar{t}$ events is modeled using PYTHIA v6.216 [8] and HERWIG v.6.510 [9]. This analysis uses the former for the final cross section estimate and the latter to estimate the systematics resulting in the modeling of $t\bar{t}$ production and decay. The PYTHIA event generator has been tuned using jet data to better model the effects of multiple interactions and remnants from the break-up of the proton and antiproton. The generators are used with the CTEQ5L parton distribution functions [10]. Decays of b - and c -hadrons are modeled using EVTGEN [11].

Events with a W boson produced in association with multiple jets are modeled using

ALPGEN v2.1 [13], with parton showering provided by PYTHIA v6.326 and HF hadron decays handled by EVTGEN. ALPGEN calculates exact matrix elements at leading order for a large set of parton level processes in QCD and electroweak interactions. The showering in PYTHIA may result in multiple ALPGEN samples covering the same phase space. These overlaps are removed using a jet-parton matching algorithm along with a jet-based heavy flavor overlap removal algorithm [12].

Estimates of backgrounds from diboson production (WW , WZ , and ZZ) and Drell-Yan/ $Z \rightarrow \tau\tau$ are derived using PYTHIA. Drell-Yan to $\mu\mu$ events are modeled using ALPGEN with PYTHIA showering while single-top production is modeled with MADEVENT [14], also with PYTHIA showering.

The CDF II detector simulation reproduces the response of the detector to particles produced in $p\bar{p}$ collisions. The detector geometry database used in the simulation is the same as that used for reconstruction of the collision data. Details of the CDF II simulation can be found in [15].

V. EFFICIENCY FOR IDENTIFYING $t\bar{t}$ EVENTS

The efficiency for identifying $t\bar{t}$ events in this analysis is factorized into the geometric times kinematic acceptance and the SLT μ tagging efficiency. The acceptance is evaluated assuming a top mass of $175 \text{ GeV}/c^2$ and includes the branching fraction to leptons, which is assumed to have the SM value. The tagging efficiency is the efficiency for SLT μ -tagging at least one jet in events that pass the geometric and kinematic selection. Each piece is described below.

A. Geometric and Kinematic Acceptance

The acceptance of $t\bar{t}$ events in this analysis is measured in PYTHIA and then corrected, using measurements from the data, for effects that are not sufficiently well modeled in the simulation: the lepton trigger efficiencies, the fraction of the $p\bar{p}$ luminous region well-contained in the CDF detector (i.e. the z -vertex cut efficiency), and track reconstruction and lepton identification efficiencies. The efficiency of the z -vertex cut, $|z_0| < 60 \text{ cm}$, is measured from minimum-bias triggered events to be $(96.3 \pm 0.2)\%$. The correction factor

for the difference between the track reconstruction efficiencies in data and simulation is 1.014 ± 0.002 . Events in the Monte Carlo are not required to pass any trigger, so the acceptance is multiplied by lepton trigger efficiency. The lepton trigger and identification efficiencies, measured using the unbiased leg of Z boson decays to electrons and muons, and the correction factors for each of the primary lepton types are shown in Tab. II.

Quantity	Electron	CMUP Muon	CMX Muon
Trigger efficiency	0.966 ± 0.005	0.917 ± 0.005	0.925 ± 0.007
Lepton ID efficiency (data)	0.789 ± 0.004	0.829 ± 0.006	0.893 ± 0.006
Lepton ID efficiency (MC)	0.806 ± 0.001	0.896 ± 0.001	0.916 ± 0.002
Lepton identification correction	0.978 ± 0.005	0.926 ± 0.007	0.975 ± 0.007

TABLE II: Summary of lepton trigger and identification efficiencies.

The raw acceptance is defined as the number of pretag events divided by the total number of $t\bar{t}$ events in the PYTHIA sample. The acceptance, after correcting for the differences between data and simulation, is shown in Tab. III as a function of the number of identified jets.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Electron (%)	0.163 ± 0.002	0.858 ± 0.004	1.63 ± 0.01	2.08 ± 0.01	3.71 ± 0.01
CMUP Muon (%)	0.088 ± 0.001	0.472 ± 0.003	0.909 ± 0.004	1.142 ± 0.005	2.05 ± 0.01
CMX Muon (%)	0.042 ± 0.001	0.219 ± 0.002	0.414 ± 0.003	0.532 ± 0.003	0.946 ± 0.004
Combined (%)	0.292 ± 0.002	1.544 ± 0.005	2.946 ± 0.008	3.743 ± 0.009	6.69 ± 0.01

TABLE III: Acceptance for $t\bar{t}$ events as a function of jet multiplicity from PYTHIA Monte Carlo sample, after data/MC corrections described in the text. In the combined acceptance we account for the fact that the CMX detector was not operating early in Run II. The uncertainties listed are statistical only.

B. Efficiency of the SLT μ Algorithm

The efficiency of the SLT μ algorithm is measured from the data using samples of J/ψ and Z decays triggered on a single muon. The tagger is applied to the non-trigger muon (probe leg). If both legs pass the trigger, only one of them is used. To reduce background in the Z sample, the leg that is not used to measure efficiency is required to be isolated and to be consistent with being a minimum ionizing particle in the calorimeter. We correct for the remaining background using the invariant mass regions outside the Z mass window (“sidebands”).

The efficiency of the SLT μ is defined as:

$$\epsilon = \frac{\text{Number of tagged muons}}{\text{Number of taggable muon tracks with a stub}}. \quad (3)$$

The requirement in the denominator that the taggable muon track has a stub in the requisite muon chambers decouples the muon reconstruction efficiency, which is accounted for separately, from the efficiency of the tagger. Figures 3 and 4 show the efficiency for tagging muons with $|L| \leq 3.5$ as a function of muon P_T from both J/ψ and Z data. The decrease in efficiency with increasing P_T is due, primarily, to non-Gaussian tails in the resolution functions. These efficiency data are fit to functional forms [4] shown as the curves in the data. The dotted curves are those obtained by varying the fit parameters by $\pm 1\sigma$. Although the efficiency measurement is dominated by isolated muons, we do not expect that it will depend on the isolation of the muon because the muon chambers are well shielded from the inner detector. We have checked this assumption by measuring the efficiency as a function of the number of nearby tracks and found no dependence.

The efficiency for SLT μ -tagging a $t\bar{t}$ event is measured for Monte Carlo events that pass the geometric and kinematic selection. We model the SLT μ tagging in these events by tagging muons from semileptonic HF decay with a probability given by the efficiencies in Figs 3 and 4. Events without a ‘real’ muon tag of this type can still be SLT μ -tagged through a mistag. Mistags in $t\bar{t}$ events are included by applying the “mistag matrix” described in the following section, and are included as part of the signal efficiency. The SLT μ tagging efficiency in $t\bar{t}$ events is given in Tab. IV.

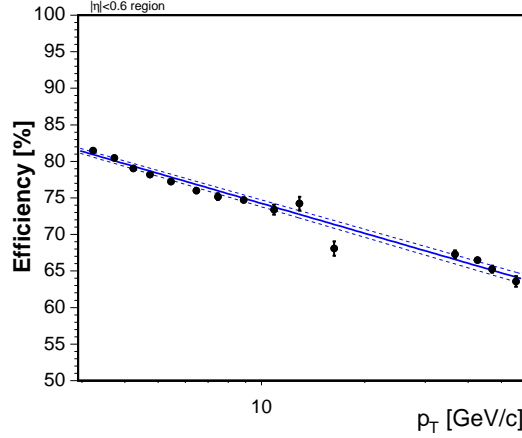


FIG. 3: The $\text{SLT}\mu$ efficiency for CMU/CMP as a function of P_T measured from J/ψ and Z data for $|L| < 3.5$. The solid line is the fit to the data and the dashed lines indicate the uncertainty on the fit.

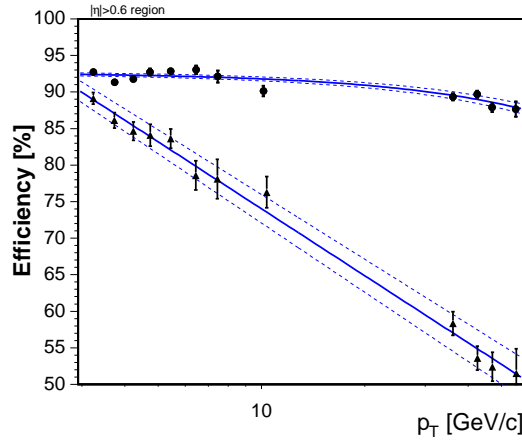


FIG. 4: The $\text{SLT}\mu$ efficiency for CMX Arches (circles) and Miniskirt/Keystone (triangles) as a function of P_T measured from J/ψ and Z data for $|L| < 3.5$. The solid curves are the fits to the data and the dashed lines indicate the uncertainties on the fits.

VI. PREDICTING THE NUMBER OF TAGS FROM LIGHT-QUARK JETS

As a prelude to the evaluation of the backgrounds to the $t\bar{t}$ signal we describe a new method, developed for this analysis, for predicting the number of $\text{SLT}\mu$ tags that come from light quark jets. We refer to these as “mistags”, and they result from a combination of

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Electron (%)	7.0 ± 0.3	11.4 ± 0.2	12.9 ± 0.1	14.9 ± 0.1	14.0 ± 0.1
CMUP Muon (%)	5.6 ± 0.3	10.7 ± 0.2	11.8 ± 0.1	14.1 ± 0.1	13.1 ± 0.1
CMX Muon (%)	6.7 ± 0.5	11.2 ± 0.3	12.3 ± 0.2	14.2 ± 0.2	13.4 ± 0.2
Average (%)	6.5 ± 0.2	11.2 ± 0.1	12.5 ± 0.1	14.6 ± 0.1	13.6 ± 0.1

TABLE IV: $t\bar{t}$ event tagging efficiency for SLT muons as a function of jet multiplicity from PYTHIA Monte Carlo sample. The lepton category refers to the primary lepton. The average tagging efficiency is determined by weighting each channel by the acceptance and luminosity for each channel. The listed uncertainties are statistical only.

hadronic punch-through of the calorimeter and muon steel, and hadronic decays-in-flight.

To predict the number of mistags in our sample we use a track-based mistag probability that is a function of track P_T and η . We use reconstructed D^* and Λ^0 to identify a clean sample of pions, kaons and protons and measure the probability per taggable track, in 8 bins of P_T and 9 bins of η , for each to satisfy the $\text{SLT}\mu \mid L \mid < 3.5$ requirement. Details of the reconstruction technique, the measurement of the tagging probabilities and the assembly and testing of the two-dimensional (8×9) “mistag matrix” are described in what follows.

A. Data samples

To identify kaons and pions we reconstruct $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$ decays, and their charge conjugates. This dataset is collected using a two-track trigger that requires two oppositely charged tracks with $P_T \geq 2$ GeV/ c . The tracks are also required to have a scalar sum $P_{T1} + P_{T2} \geq 5.5$ GeV/ c , an opening angle between them of $2^\circ \leq |\Delta\phi| \leq 90^\circ$, and originate from a displaced vertex.

A sample of protons is obtained by reconstructing $\Lambda \rightarrow p \pi^-$ decays. These events are collected using another two-track trigger similar to the one described above, but with an opening angle requirement of $20^\circ \leq |\Delta\phi| \leq 135^\circ$ and the invariant mass of the track pair (assumed to be pions) required to be $4 \text{ GeV}/c^2 \leq M(\pi, \pi) \leq 7 \text{ GeV}/c^2$.

B. Event Reconstruction

We apply the following track quality criteria in the reconstruction of both D^* [16] and Λ^0 [17] decays:

- the number of COT axial superlayers with ≥ 5 hits is ≥ 3 ;
- the number of COT stereo superlayers with ≥ 5 hits is ≥ 2 ;
- the track has $|z_0| \leq 60$ cm.

The D^* reconstruction then proceeds through the examination of the mass difference $\Delta m = m(K\pi\pi) - m(K\pi)$ with the following criteria:

- the kaon must have opposite charge to each of the two pions;
- $|\Delta z_0| \leq 5$ cm between any two tracks;
- the soft pion from the $D^* \rightarrow D^0\pi$ decay must have $P_T \geq 0.5$ GeV/c;
- the kaon and pion from the D^0 decay must each have $P_T \geq 2$ GeV/c;
- the kaon and pion tracks must have impact parameter, $|d_0| \leq 0.2$ cm;
- $|m(K\pi) - m(D^0)| \leq 0.03$ GeV/ c^2 ;
- At least one of the tracks (K or π) from the D^0 must be SLT μ taggable (including having $P_T \geq 3$ GeV/c).

As shown in Fig. 5, a clean D^* signal is obtained for the right-sign Δm distribution.

The reconstruction of Λ decays requires the following criteria:

- the pion and proton must have opposite charge;
- $|\Delta z_0| \leq 2$ cm between the two tracks;
- the χ^2 of the vertex fit must be ≤ 10 ;
- the vertex must have $L_{xy} \geq 0.5$ cm, where L_{xy} is defined as the projection onto the net momentum direction, in the $r - \phi$ plane, of the vector pointing from the primary to the secondary vertex.;

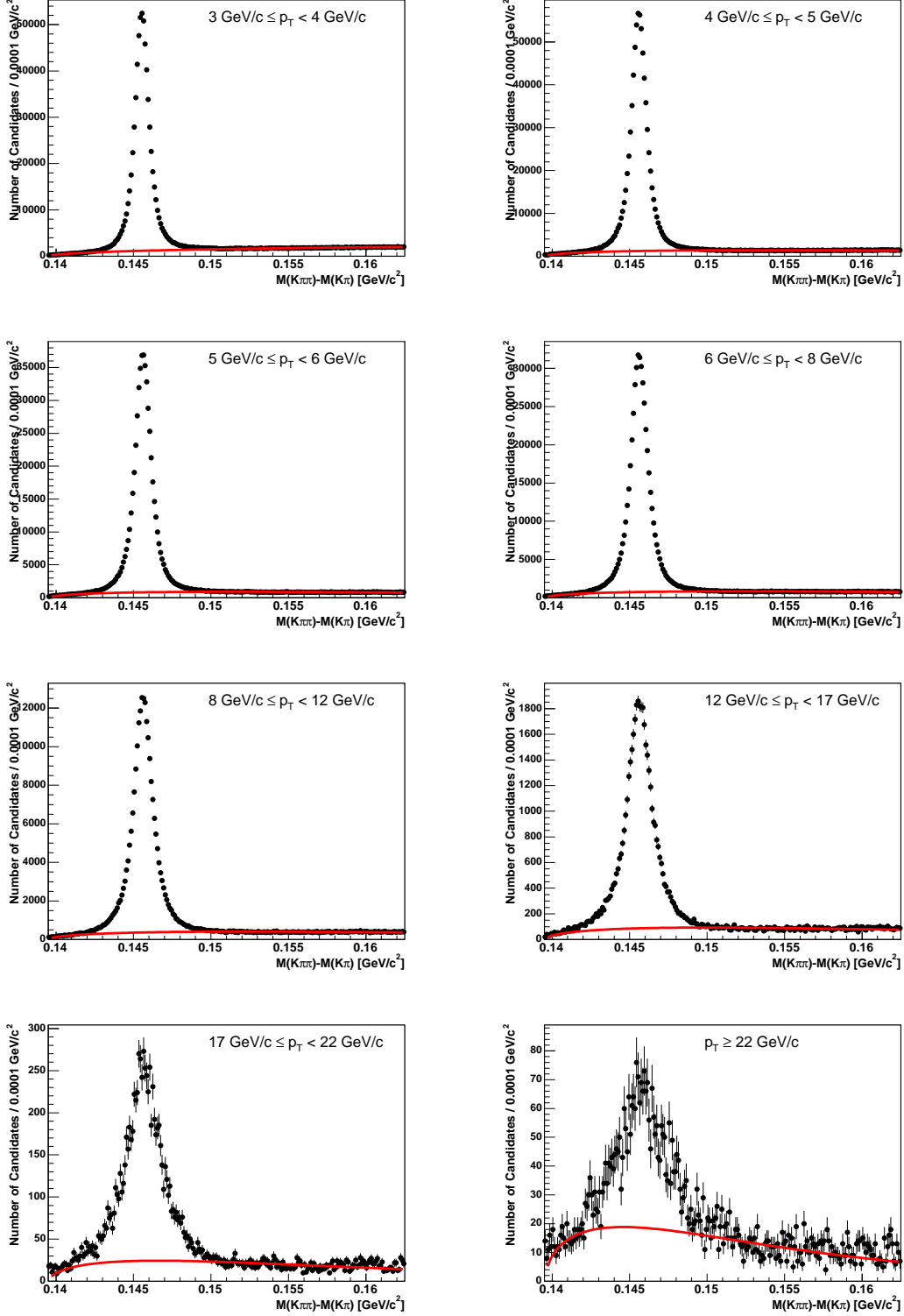


FIG. 5: The $m(K\pi\pi) - m(K\pi)$ distribution for $D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^\mp\pi^\pm$ candidates in different SLT μ -track- P_T bins. The line in each plot represents the fit to the sideband regions.

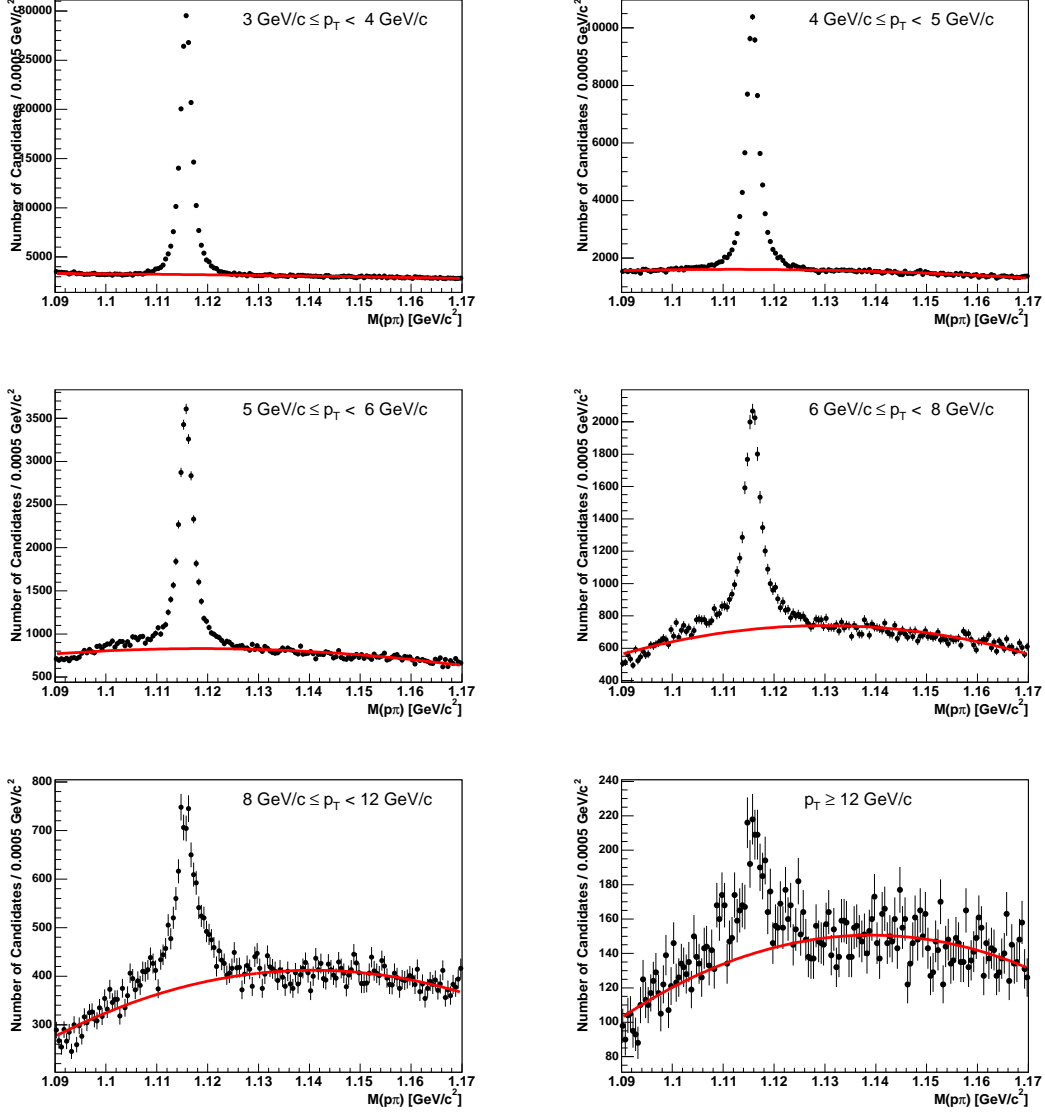


FIG. 6: The $m(p\pi)$ distribution for $\Lambda^0 \rightarrow p\pi$ candidates in different SLT μ -track- P_T bins. The line in each plot represents the fit to the sideband regions.

- the proton P_T is greater than the pion P_T ;
- the pion must have $P_T \geq 0.4$ GeV/c;
- the proton must have $|d_0| \leq 0.2$ cm;
- the proton must be SLT μ taggable (including having $P_T \geq 3$ GeV/c).

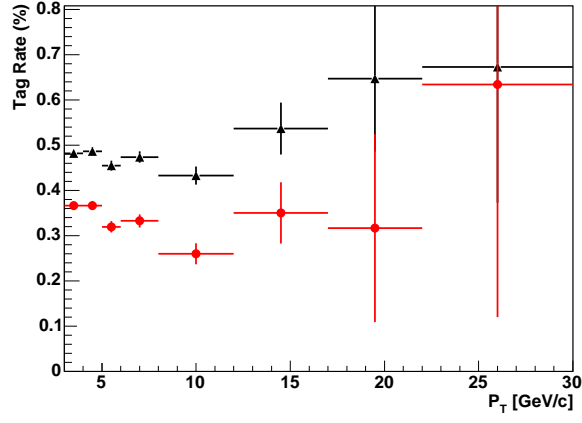
Figure 6 shows the invariant mass distribution in the $p\pi$ mass hypothesis.

Region	Mass Window (MeV/c ²)
D^* Signal	$142.421 < \Delta m < 148.421$
D^* Sidebands	$139.6 < \Delta m < 141$ or $152 < \Delta m < 162.5$
Λ^0 Signal	$1109.683 < m < 1121.683$
Λ^0 Sidebands	$1090 < m < 1105.683$ or $1125.683 < m < 1170$

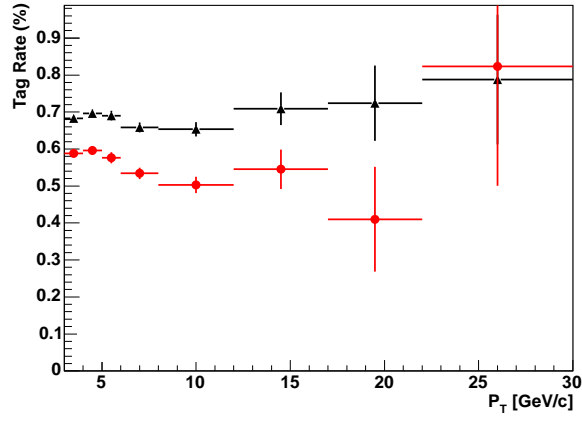
TABLE V: Mass windows used in determining the status of a D^* or Λ^0 candidate.

We define a signal region for D^* and Λ^0 decays as well as sideband regions for each. We measure the sideband-subtracted tagging probability for K , π and p tracks using events in the signal, corrected for the enhanced probabilities in the sidebands. The sideband regions have a higher SLT μ per track tag probability because they are enriched in HF as a result of the two-track trigger described above. The signal and sideband regions are given in Tab. V and the sideband subtraction is done using the fits [5] shown in Figs 5 and 6. The tag probabilities before and after sideband subtraction are shown as a function of P_T in Fig. 7. We note that there are systematic uncertainties due to the choice of fit functions and in particular the quality of the fits in the sideband regions. These systematics, and all others associated with the construction of the mistag matrix, are evaluated by testing the predictive power of the matrix on a variety of independent data samples, as described in Section VIII B.

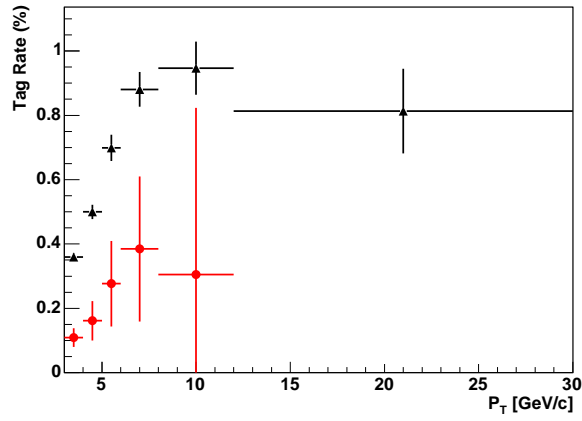
The mistag matrix is designed to predict SLT μ tags that arise from both hadronic punch-through and decays-in-flight. When a pion or a kaon from a D^* decays in flight, the track may be poorly reconstructed causing the reconstructed mass to fall outside of the signal region defined in Tab. V. We measure the size of this effect using D^* decays in a Monte Carlo sample and make a correction. The correction factor is calculated in three bins in P_T (limited by the sample size of the Monte Carlo) and shown in Tab. VI. Full details of the calculation of the correction factor are given in [5].



(a)



(b)



(c)

FIG. 7: The measured (triangles) and sideband-subtracted (circles) tag probabilities as a function of track P_T for (a) pions, (b) kaons, and (c) protons. The uncertainties shown are statistical only.

	P_T	Frac. DIF	After Reco. DIF	Tag prob.	Corr. Factor
	[GeV/c]	[%]	[%]	[%]	
π	3–4	0.40 ± 0.05	0.20 ± 0.04	44.6 ± 2.0	1.25 ± 0.08
	4–6	0.25 ± 0.04	0.16 ± 0.03	60.1 ± 2.3	1.16 ± 0.08
	> 6	0.20 ± 0.04	0.16 ± 0.04	75.6 ± 2.6	1.09 ± 0.14
K	3–4	0.99 ± 0.09	0.77 ± 0.08	10.2 ± 1.3	1.04 ± 0.02
	4–6	0.65 ± 0.06	0.51 ± 0.06	10.8 ± 1.3	1.02 ± 0.02
	> 6	0.39 ± 0.05	0.23 ± 0.04	18.2 ± 1.8	1.05 ± 0.02

TABLE VI: Relevant numbers, from Monte Carlo simulation, in the determination of the decay-in-flight correction for D^* decays. These include the fraction of taggable tracks from D^* s that decay-in-flight (DIF), the same fraction after all reconstruction requirements that fall inside the D^* signal window (shown in Tab. V) and the probability for tagging a decay-in-flight. The last column gives the correction factor that is applied to the measured tag probability to account for the bias against decays-in-flight.

C. The Mistag Matrix

At this point we have SLT μ tag probabilities for tracks from π , K and p , corrected for backgrounds (sideband-subtracted) and for a bias against π and K decays-in-flight. What remains is to assemble these separate SLT μ tag probabilities into a full mistag matrix that can be used to predict the number of tags in light-flavor jets in W +jets events.

To assemble the final mistag matrix, we take a weighted sum of the individual π , K and p matrices as follows:

$$M_{ij} = W_\pi \cdot M_{ij}^\pi + W_K \cdot M_{ij}^K + W_p \cdot M_{ij}^p. \quad (4)$$

where M_{ij} is the entry in the i^{th} P_T and j^{th} η bin of the final matrix and M_{ij}^π , M_{ij}^K and M_{ij}^p are the corresponding entries in the π , K and p matrices. The weights $W_\pi = 71.9\%$, $W_K = 15.6\%$ and $W_p = 12.5\%$, are taken from the taggable-track particle content of light-quark jets in ALPGEN W +jets Monte Carlo. Figure 8 shows the final tag probability for the eight P_T bins (integrated over η) and the nine η bins (integrated over P_T). The features in the η distribution are due to the profile of absorber in front of, and the coverage of, the

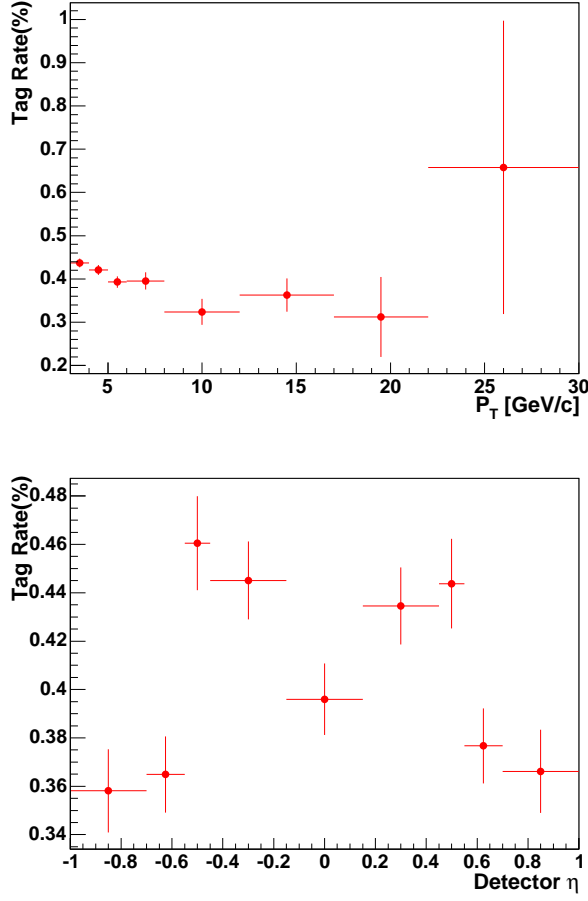


FIG. 8: The mistag probability per track as a function of track P_T and detector η . The histogram binning matches that of the matrix. The uncertainties shown are statistical only. The structure in the η distribution is an artifact of the profile of the absorber and geometrical coverage of the muon system.

muon system. The average tag probability per track in the matrix is $(0.41 \pm 0.01)\%$ per track.

The uncertainties associated with the probabilities in the mistag matrix include uncertainties from the sideband subtraction, the decay-in-flight correction and the weighting of π , K and p probabilities, to name just a few. To evaluate the overall systematic uncertainty on the number of light-quark tags predicted by the matrix, one possibility would be to carefully evaluate the size of each of these uncertainties. However, there is no straightforward way to do this. Instead, as described in detail in Section VIII B, we directly test the predictive

power of the matrix, using event samples acquired with jet triggers, and use the control samples of $W + 1$ and 2 jet events to further validate the technique and establish that we have not underestimated the size of the systematic uncertainty.

VII. BACKGROUND EVALUATION

The dominant background contribution to the $t\bar{t}$ signal in this analysis comes from mistags in W +jets events. Another smaller, yet still significant background comes from W bosons produced in association with heavy flavor ($Wb\bar{b}$, $Wc\bar{c}$ and Wc). The estimate of the mistag background is described in Section VII A, while the W +HF background estimate is described in Section VII B.

Other backgrounds that can produce a W boson and an SLT μ tag that are not accounted for by the mistag matrix include dibosons (WW , ZZ , WZ), $Z \rightarrow \tau^+\tau^-$, single top, QCD multijet backgrounds including $b\bar{b}$, and residual Drell-Yan ($\mu\mu$) events not removed by the dimuon removal. QCD and Drell-Yan backgrounds are measured using the data, as described in detail in Sections VII C and VII D below. The remaining backgrounds are estimated from Monte Carlo as described in Section VII E. We treat QCD independently of the calculation of mistags in W +jets events because events that enter our sample by mimicking the signature of a W boson can have a significantly larger tag rate than true W events. The enhanced tag rate arises due to the contribution of $b\bar{b}$ events to the QCD background and because of the correlation between the tag rate and measured \cancel{E}_T in events in which the \cancel{E}_T arises from jet mismeasurement or semileptonic HF decay rather than from a neutrino in a W boson decay. In order to avoid double counting we correct the estimate of tags in W +jets events by $(1 - F_{QCD})$, where F_{QCD} is the QCD multijet fraction in the W +jets candidate sample.

A. Mistags

The background due to mistags is evaluated using the track-based mistag matrix described in Section VI. To predict the number of events from W +jets with at least 1 mistag, we apply the mistag matrix to all pretag events according to:

$$N_{\text{raw}}^{W\text{jtag}} = \sum_{\text{events}} \left[1 - \prod_{i=1}^{N_{\text{trk}}} (1 - \mathcal{P}(P_{Ti}, \eta_i)) \right], \quad (5)$$

where the sum runs over each event in the pretag sample, and the product is over each taggable track in the event. $\mathcal{P}(P_{Ti}, \eta_i)$ is the probability from the mistag matrix for tagging the i^{th} track with parameters P_{Ti} and η_i . Note that the sum over the events in equation 5 includes any $t\bar{t}$ events that are in the pretag sample. We correct for the resulting overestimate of the background at the final stage of the cross section calculation (see Section IX). It also includes W +HF events, diboson events, etc. Therefore mistags from these backgrounds are included here. Tags from muons resulting from the decay of HF hadrons or W or Z bosons in these backgrounds are calculated separately using Monte Carlo simulations, as described in Sections VII B and VII E. To avoid any double counting the Monte Carlo estimates of the contributions from these backgrounds do not include any mistags.

A fraction, F_{QCD} , of the events in the signal region are QCD events for which the background is estimated separately. Therefore, we correct the prediction of equation 5 according to

$$N_{\text{corr}}^{Wjtag} = (1 - F_{QCD}) \cdot N_{\text{raw}}^{Wjtag}. \quad (6)$$

The background estimate from the application of the mistag matrix is shown in Tab. VII. We list here both the raw prediction and that corrected by $(1 - F_{QCD})$. The calculation of F_{QCD} is described in Section VII C 1.

	1 jet	2 jet	3 jets	≥ 4 jets	≥ 3 jets
N_{raw}^{Wjtag}	641 \pm 32	238 \pm 12	55.0 \pm 2.8	32.7 \pm 1.6	87.5 \pm 4.4
N_{corr}^{Wjtag}	622 \pm 31	226 \pm 12	53.0 \pm 2.7	31.4 \pm 1.6	84.5 \pm 4.3

TABLE VII: Summary of background estimate from mistags in W +jets events. These numbers include a contribution from $t\bar{t}$ events in the W +jets sample that is removed in the final cross section calculation, as described in Section IX

B. W +Heavy Flavor

The evaluation of background tags from the semileptonic decays of HF quarks in $Wb\bar{b}$, $Wc\bar{c}$ and Wc events is done using the ALPGEN Monte Carlo program. We determine the fraction of W +jets events that contain heavy flavor at the pretag level, F_{HF} , and the tagging

efficiency, ϵ_{HF} , for these events and then normalize the total to the number of W +jets events seen in the data. The final prediction of the number of tags from W +heavy-flavor events is:

$$N_{HF} = (1 - F_{QCD} - F_{other}) \cdot N_{pretag} \cdot F_{HF} \cdot \epsilon_{HF}. \quad (7)$$

where F_{QCD} is the fraction of QCD events in the pretag sample and F_{other} is the fraction of other, non- W +jets backgrounds. As with the mistag prediction, correction for $t\bar{t}$ in the pretag sample is done as part of the final cross section calculation.

This procedure is used because the theory cross sections for the $Wb\bar{b}$, $Wc\bar{c}$ and Wc processes have large uncertainties, whereas the uncertainties on the fraction of events with heavy-flavor jets are smaller. This procedure follows that used in [3].

1. Heavy-Flavor Fractions & Tagging Efficiency

The HF fractions of events in the W +jets sample are determined by measuring the fractions in Monte Carlo and then scaling those fractions by a multiplicative factor of 1.15 ± 0.35 , determined by comparing measured HF fractions in inclusive jet data with those predicted by ALPGEN.

The ALPGEN HF fractions, broken down according the number of b - or c -jets, are shown in Tab. VIII. In addition to the uncertainty on the HF-fraction scaling, an additional uncertainty on the ALPGEN fractions is determined by varying the ALPGEN generator parameters such as Q^2 and the quark masses.

The Monte Carlo is also employed to determine the efficiency for tagging a muon from a semileptonic heavy-flavor decay in W +heavy-flavor events. As with the $t\bar{t}$ tagging efficiency described in Section V, tags are assigned based on the SLT μ tagging efficiency measured in the data (Fig. 3 and 4). The results are shown in Tab. VIII. Note that we do not include here the additional efficiency that arises from mistags in real HF jets, because this is included in the mistag evaluation given in Tab. VII.

Armed with these HF fractions and tagging efficiencies, the number of tagged events from W +HF is evaluated according to equation 7 above. The results are given in the last line of Tab. VIII.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Category 2 b					
F_{HF} (%)		0.9 ± 0.3	1.8 ± 0.7	2.8 ± 1.1	2.0 ± 0.8
ϵ_{HF}		7.8 ± 0.2	8.4 ± 0.2	8.5 ± 0.3	8.4 ± 0.2
Category 1 b					
F_{HF} (%)	0.7 ± 0.3	1.4 ± 0.5	2.6 ± 1.0	3.0 ± 1.1	2.7 ± 1.0
ϵ_{HF}	3.54 ± 0.05	4.30 ± 0.06	5.5 ± 0.1	5.8 ± 0.2	5.53 ± 0.09
Category 2 c					
F_{HF} (%)		1.3 ± 0.5	2.8 ± 1.1	4.5 ± 1.7	3.1 ± 1.2
ϵ_{HF}		3.1 ± 0.1	3.6 ± 0.1	3.5 ± 0.2	3.6 ± 0.1
Category 1 c					
F_{HF} (%)	5.5 ± 2.1	8.9 ± 3.4	11.0 ± 4.1	11.5 ± 4.4	11.1 ± 4.2
ϵ_{HF}	1.52 ± 0.02	1.70 ± 0.03	2.04 ± 0.07	2.05 ± 0.06	2.04 ± 0.06
$Wb\bar{b}+Wc\bar{c}+Wc$ Background	145 ± 55	66.6 ± 25.2	15.3 ± 5.8	8.5 ± 3.2	23.0 ± 8.7

TABLE VIII: The heavy-flavor fractions, F_{HF} , tagging efficiencies, ϵ_{HF} , and W +heavy-flavor background evaluated using ALPGEN Monte Carlo. The fractions are scaled by 1.15 as described in the text. The uncertainty on the heavy-flavor fractions includes that from the scaling factor and from variation of the ALPGEN parameters.

C. QCD Background

The background due to tags in QCD events that enter the signal sample is estimated by calculating the fraction of QCD events in the W +jets data and applying the standard mistag matrix times a multiplicative factor. The multiplicative factor is required because the tagging rate of QCD events that enter the pretag sample is higher than the corresponding tagging rate for W +jets events.

1. The QCD Fraction

The fraction of QCD events before $\text{SLT}\mu$ tagging is determined using the isolation, I (see Section III A), and \cancel{E}_T of events with high- P_T leptons and jets. Under the assumption that I and \cancel{E}_T are uncorrelated for QCD events, the number of QCD events in the $t\bar{t}$ signal region can be found by extrapolation from the non-signal regions

$$N_D^{QCD} = \frac{N_C}{N_A} N_B, \quad (8)$$

Where region D , the signal region, and regions A, B and C are defined according to

Region A : $\cancel{E}_T < 20$ GeV; $I > 0.2$

Region B : $\cancel{E}_T < 20$ GeV; $I < 0.1$

Region C : $\cancel{E}_T > 30$ GeV; $I > 0.2$

Region D : $\cancel{E}_T > 30$ GeV; $I < 0.1$.

The event counts used in equation 8 are corrected for Monte Carlo predictions of the number of W +jets and $t\bar{t}$ events in Regions A, B and C . The QCD fraction, F_{QCD} is then given by N_D^{QCD} divided by the total number of events in Region D. The QCD fractions are given in Tab. IX.

To evaluate the accuracy of the \cancel{E}_T - I prediction, two complementary regions in the plane are defined as:

Region E : $\cancel{E}_T < 20$ GeV; $0.1 < I < 0.2$

Region F : $\cancel{E}_T > 30$ GeV; $0.1 < I < 0.2$.

The different regions in the \cancel{E}_T - I plane are shown in Fig. 9. Region F is outside the signal region and, once contamination from W +jets and $t\bar{t}$ is removed, should have a QCD fraction, F_{QCD}^F , of approximately 1.0. F_{QCD}^F is given by:

$$F_{QCD}^F = \frac{N_C \cdot N_E}{N_A \cdot N_F}. \quad (9)$$

We use the difference of F_{QCD}^F from 1.0 to estimate a systematic uncertainty on the \cancel{E}_T vs. I technique. The results are given in Tab. IX. Given the deviation from 1.0 in the ≥ 3 jets data, we assign an 11% (120%) systematic uncertainty to F_{QCD} for electrons (muons).

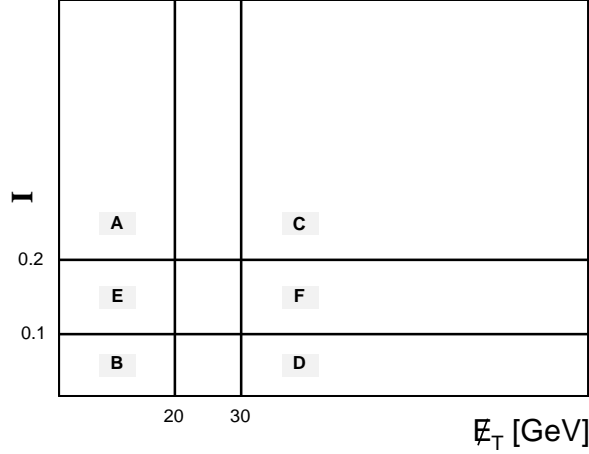


FIG. 9: A diagram illustrating the regions defined in the E_T vs. I plane.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Electron channel					
F_{QCD}	0.0423 ± 0.0009	0.070 ± 0.002	0.049 ± 0.003	0.056 ± 0.006	0.051 ± 0.003
Region F	0.95 ± 0.04	0.97 ± 0.06	0.84 ± 0.10	1.06 ± 0.24	0.89 ± 0.09
Muon channel					
F_{QCD}	0.0118 ± 0.0004	0.020 ± 0.001	0.013 ± 0.004	0.007 ± 0.004	0.011 ± 0.003
Region F	0.58 ± 0.05	0.65 ± 0.07	0.31 ± 0.09	2.27 ± 4.25	0.45 ± 0.13

TABLE IX: The fractions, F_{QCD} , of lepton-plus-jets events due to QCD multijet processes before SLT μ tagging. The uncertainties on the F_{QCD} values are statistical only. Also shown is the measured QCD fraction in Region F, used to assign a systematic uncertainty on the F_{QCD} prediction.

2. The Tag Rate of QCD Events

The tag rate in QCD events that populate our signal region is enhanced relative to the rate predicted by the mistag matrix. There are two sources for this enhancement. First, much of the E_T in QCD events is due to mismeasurement of jet energies, which is correlated

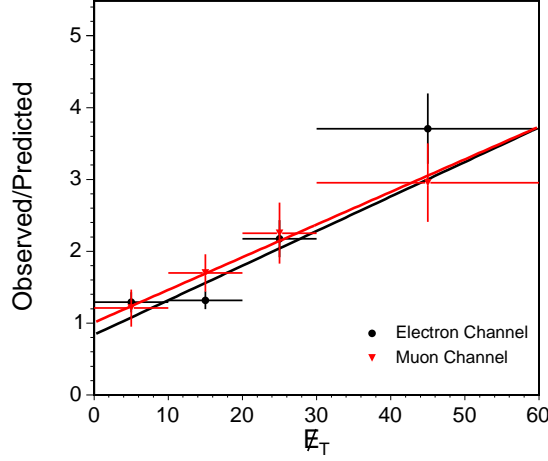


FIG. 10: The ratio of observed to predicted tags as a function of E_T in data with a non-isolated primary lepton ($I \geq 0.2$).

with the tag rate (see Section VIII B). As seen in Fig. 10, the ratio of observed to predicted tags increases with E_T . Second, QCD includes $b\bar{b}$ and $c\bar{c}$ events in which the high- P_T lepton comes from the semileptonic decay of one of the b or c quarks; if the other also decays semileptonically, it may be tagged by the SLT μ .

In the E_T - I plane, the region closest kinematically to the signal region (Region D) is the high-isolation and high- E_T region, Region C. Region C has the same E_T requirement that Region D does, and likewise it requires a high- P_T lepton in the event. Therefore, the tag rate measured in Region C is a good representation of that of QCD events in Region D.

The tag rate of QCD events is measured as an enhancement factor, k , times the W +jets mistag probability. We calculate k as the ratio of observed to predicted (by the mistag matrix) SLT μ tags in Region C. The results are shown in Tab. X.

3. The QCD Background Estimate

Having determined F_{QCD} and k , the QCD background is given by:

$$N_{QCD} = N_{\text{raw}}^{\text{Wjtag}} \cdot k \cdot F_{QCD} \quad (10)$$

where $N_{\text{raw}}^{\text{Wjtag}}$ comes from equation 5.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
Electron channel					
F_{QCD}	0.042 ± 0.005	0.070 ± 0.008	0.051 ± 0.006		
k	5.3 ± 0.4	3.9 ± 0.4	3.7 ± 0.5		
N_{QCD}	82.6 ± 11.9	38.1 ± 6.1	6.3 ± 1.2	3.6 ± 0.7	9.9 ± 1.9
Muon channel					
F_{QCD}	0.0118 ± 0.0004	0.0205 ± 0.0009	0.011 ± 0.014		
k	2.9 ± 0.4	3.4 ± 0.4	3.0 ± 0.5		
N_{QCD}	9.3 ± 11.3	6.8 ± 8.3	0.7 ± 0.9	0.4 ± 0.6	1.2 ± 1.4
Combined channels					
Total N_{QCD}	92 ± 17	44.9 ± 10.4	7.0 ± 1.5	4.1 ± 0.9	11.1 ± 2.4

TABLE X: Summary of the QCD background estimate. The uncertainties on the QCD fractions, F_{QCD} , and on the number of QCD events, N_{QCD} , are systematic and statistical combined. The F_{QCD} and k values in the third column apply to 3, ≥ 4 and ≥ 3 jets.

D. Drell-Yan $\rightarrow \mu\mu$

Drell-Yan $\rightarrow \mu\mu$ events can survive the Z , Υ and J/ψ vetoes if one muon leg fails the isolation requirement. We evaluate the number of residual Drell-Yan events that remain in the signal sample after the dimuon vetoes by measuring the number of $Z \rightarrow \mu\mu$ events in the data, N_{tag}^Z , inside the Z mass window, where one leg of the Z is identified as an SLT μ (these events are normally removed from the signal sample). We then use an ALPGEN $Z/\gamma^* \rightarrow \mu\mu$ Monte Carlo sample to estimate the ratio, $R^{out/in}$, of events outside the Z -mass window to events inside. To increase the statistical precision the ratio is measured with the E_T and H_T and dilepton rejection cuts removed and without requiring that the SLT μ be inside a jet. We use the Monte Carlo to measure the ratio of efficiencies $\epsilon^{out}/\epsilon^{in}$ of these requirements.

With these pieces, the number of residual Drell-Yan events, N_{DY} is

$$N_{DY} = N_{tag}^Z \cdot R_{in}^{out} \cdot \frac{\epsilon^{out}(\cancel{E}_T, H_T, \text{dilep}, \text{SLT-jet})}{\epsilon^{in}(\cancel{E}_T, H_T, \text{dilep}, \text{SLT-jet})}, \quad (11)$$

The results of the Drell-Yan calculation are given in Tab. XI.

	1 jet	2 jets	3 jets	≥ 4 jets	≥ 3 jets
N_{tag}^Z (data)	27	25	3	0	3
R_{in}^{out}	0.325 ± 0.003	0.315 ± 0.005		0.312 ± 0.006	
ϵ^{out} (%)	0.71 ± 0.04	1.62 ± 0.10		2.85 ± 0.24	
ϵ^{in} (%)	1.03 ± 0.05	3.10 ± 0.12		3.24 ± 0.18	
$R_{in}^{out} \cdot \frac{\epsilon^{out}}{\epsilon^{in}}$	0.223 ± 0.018	0.165 ± 0.013		0.274 ± 0.027	
Drell-Yan Total	6.02 ± 1.25	4.12 ± 0.88	0.82 ± 0.44	0.00 ± 0.19	0.82 ± 0.48

TABLE XI: Drell-Yan background summary. Uncertainties are statistical only. The values in the third column apply to 3, ≥ 4 and ≥ 3 jets.

E. Monte Carlo Driven Backgrounds

Backgrounds from dibosons (WW , WZ , ZZ), $Z \rightarrow \tau^+ \tau^-$, and single top are determined from Monte Carlo. For each of these backgrounds, the estimated number of tags is calculated as

$$N_i = \sigma_i \cdot A_i \cdot \epsilon_i \cdot \int L dt. \quad (12)$$

Here σ_i is the theoretical cross section. The acceptance, A_i , and the SLT μ tagging efficiency, ϵ_i , are calculated from the Monte Carlo. As with the W +HF evaluation in Section VII B, the efficiency includes only that due to tagging a muon from a semileptonic heavy-flavor decay. We do not include mistags in the efficiency evaluation because this is included as part of the background determined by the mistag matrix. The background evaluations are shown in Tab. XII.

VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis come from Monte Carlo modeling of the geometrical and kinematic acceptance, knowledge of the SLT μ tagging efficiency, the effect on

the acceptance of the uncertainty on the jet energy scale, uncertainties on the background predictions, and the uncertainty on the luminosity. The evaluation of the size of each of these uncertainties is described below.

A. Systematic Uncertainties on Acceptance and Efficiency

Monte Carlo modeling of geometrical and kinematic acceptance includes effects of parton distribution functions (PDFs), initial-state radiation (ISR), final-state radiation (FSR), and jet energy scale. These are estimated by comparing different choices for PDFs, varying ISR, FSR and the jet energy scale in the Monte Carlo and comparing the PYTHIA generator with HERWIG.

The PDF uncertainty is evaluated from 3 contributions. The first is obtained by varying the PDF according to the 20 CTEQ eigenvectors [10] to account for the uncertainty on the PDF fit. The second is the difference between the CTEQ5L PDF used for the acceptance measurement with that obtained using MRST98 [22] in the default configuration to account for the type of PDF fit used. The third is evaluated comparing the default MRST with two alternative choices of α_s to get an estimate of the uncertainty due to the value of α_s . The three contributions in quadrature yield an acceptance uncertainty of 0.9%.

The uncertainty due to the limited knowledge of ISR is constrained by studies of radiation in Drell-Yan events in the data. We vary both ISR and FSR in the $t\bar{t}$ Monte Carlo within the allowed range and add the deviations in quadrature. The systematic uncertainty due to this effect is 0.8%.

The uncertainty on the acceptance due to the uncertainty in the jet energy scale is measured by shifting the energies of the jets in $t\bar{t}$ Monte Carlo by $\pm 1\sigma$ of the jet energy scale [18]. The resulting uncertainty on the acceptance is 4.1%.

The effects of generator modeling of the $t\bar{t}$ kinematics are measured by comparing the acceptance from PYTHIA and HERWIG. The result is a 2.4% uncertainty.

As described in Section V A, a scale factor is applied to the $t\bar{t}$ Monte Carlo data set to correct for lepton ID efficiency differences between data and Monte Carlo. This scale factor has an associated uncertainty that yields a 2.9% uncertainty on the total $t\bar{t}$ acceptance.

The systematic uncertainty on the $SLT\mu$ tagging efficiency in $t\bar{t}$ events is comprised of three parts. First, the uncertainty due to the P_T dependence of the $SLT\mu$ efficiency curves

which is evaluated by remeasuring the $t\bar{t}$ event tagging efficiency with the $\pm 1\sigma$ curves shown as the dashed lines in Fig. 3 and 4. Next, the tagging efficiency measurement assumes that the efficiency for finding tracks in jets in the COT is properly modeled in the simulation. This assumption comes with a 5% uncertainty, which was evaluated by embedding MC tracks in data events. Finally, the statistical uncertainty on the $\text{SLT}\mu$ efficiency in $t\bar{t}$ events is absorbed as a systematic uncertainty. The three contributions combine to give a systematic uncertainty of 5.1%.

Adding all these contributions in quadrature gives a total “Acceptance Modeling and Efficiency” systematic uncertainty of 7.7%.

B. Systematic Uncertainty of the Mistag Prediction

To measure the uncertainty on the predicted number of tags in light-flavor jets, we test the predictive power of the mistag matrix on large samples of events triggered on a single jet with an (uncorrected) E_T threshold of 20, 50, 70 or 100 GeV. Care must be taken in several areas. Because of the E_T threshold on one jet in the event, that ‘trigger jet’ will have a bias against $\text{SLT}\mu$ tags because particles that reach the muon chambers do not deposit all their energy in the calorimeter and therefore reduce the measured jet energy from its true value. Therefore, if no other jet is above the trigger threshold, we remove the trigger jet from the sample used to test the mistag prediction. If there is an additional jet above the trigger threshold, then all jets above threshold are used. The opposite effect occurs in jets that are measured well below trigger threshold. In a di-jet event triggered, for instance, with a 100 GeV threshold, a single recoil jet with energy well below 100 GeV is likely to be significantly mis-measured. Such jets have an enhanced rate of $\text{SLT}\mu$ tags relative to jets in W +jets events because jet mis-measurement is correlated with the population of $\text{SLT}\mu$ tags through detector cracks, hadronic punch-through of the calorimeter and real muon content. In addition to rejecting the trigger jet, we reject jets in di-jet events if the recoil jet falls below the trigger threshold. For events with higher jet multiplicities we use only tracks in jets that are separated from the trigger-jet axis by ΔR between 0.7 and 2.6. These various criteria have been chosen in order to provide, in the jet samples, a set of jets that are similar in terms of $\text{SLT}\mu$ tags to those found in W +jets events [5].

To increase the number of jets available for the study we use, in addition to the jet

triggered data, events triggered on a single photon candidate (γ +jets) with a threshold of 25, 50 or 70 GeV, and a ΣE_T -triggered sample, triggered on a four-jet total energy of at least 100 GeV. Jets in the γ +jets events are selected in the same way as in the single jet triggered events. All jets above 20 GeV are used in the ΣE_T sample.

Since the mistag matrix is designed to predict the number of tags from light-flavor jets, we must also suppress heavy-flavor jets in our sample. This is achieved by removing events in which any jet has an identified secondary vertex [3], or in which the mass of the tracks contained in a potential secondary vertex is greater than $0.3 \text{ GeV}/c^2$, or in which any jet contains a track with an impact parameter significance $(d_0/\sigma_{d_0}) \geq 2$. This is found [5] to provide sufficient suppression of heavy-flavor jets while leaving the remaining sample unbiased against decays-in-flight inside the jet.

With the above jet selection, the systematic uncertainty is determined using the difference between the number of SLT μ tags predicted by the mistag matrix and those observed in the data. The results are shown, as a function of the E_T of the jet in Tab. XIII.

Finally, we use the E_T spectrum of W +jets events from the Monte Carlo to perform a weighted average over the deviations between predicted and observed tags given in Tab. XIII. The result is $(\text{Predicted SLT}\mu - \text{Observed SLT}\mu)/\text{Pred.} = (0.1 \pm 4.4)\%$. We assign a systematic uncertainty of 5% on the prediction of the mistag matrix.

C. Other Background Uncertainties

1. W + Heavy Flavor Uncertainties

Three sources contribute to the uncertainty on the $Wb\bar{b} + Wc\bar{c} + Wc$ background prediction: the choice of ALPGEN settings, the uncertainty associated with the scaling factor that takes the heavy-flavor fraction in ALPGEN to the data, and the uncertainty on the tagging efficiency. The determination of the uncertainties on the ALPGEN settings and the scale factor are described in Section VII B. The ALPGEN settings contribute 23% to the W +heavy-flavor background uncertainty and the scale factor another 13%. The uncertainty on the heavy-flavor tagging efficiency is the same as that for the $t\bar{t}$ tagging efficiency described in Section VIII A. The correlation between the efficiency for the background determination and for the $t\bar{t}$ acceptance is taken into account.

2. *QCD Background Uncertainties*

Uncertainties on the QCD background prediction are determined using the level of agreement between predicted and measured events in ‘Region F’, as described in Section VII C 1. We assign a systematic uncertainty on the F_{QCD} measurement of 11% for electrons and 120% for muons, given conservatively by the worst agreement of the Region F prediction in each case. We fold this in with the statistical uncertainty on the F_{QCD} determination, the uncertainty on the correction factor k , both given in Tab. X, and the 5% systematic uncertainty due to the application of the mistag matrix. The total QCD background uncertainty is 19% and 124% for electrons and muons, respectively. In the final determination of the QCD systematic, we add in quadrature the separate effects on the cross section of the QCD uncertainties for electrons and muons. The estimate of the QCD background is correlated with the estimates of the mistags and W +heavy-flavor backgrounds (equations 6, 7, and 10). This is taken into account when determining the effect on the $t\bar{t}$ cross section. Together with a relatively small QCD fraction of the events, the result is a rather small effect on the cross section determination, despite the large uncertainty on the QCD fraction itself.

3. *Other Background Uncertainties*

The systematic uncertainty on the small Drell-Yan background is determined by the statistical uncertainty of the estimate. Uncertainties on the Monte Carlo background predictions come from uncertainties in the cross sections for the various processes and from the event sizes of the Monte Carlo samples. This uncertainty is reflected in the uncertainties quoted in Section VII E. The combined uncertainty on the Drell-Yan and Monte-Carlo-derived backgrounds is 11%.

D. **Summary of Systematic Uncertainties**

The systematic uncertainties are summarized in Tab. XIV. An additional systematic due to the uncertainty on the luminosity determination (5.9% [7]), is treated separately.

IX. $t\bar{t}$ PRODUCTION CROSS SECTION

Before calculating the cross section, the estimated number of background events is corrected for $t\bar{t}$ events in the pretag sample using a simple iterative procedure. This is required because we apply the mistag matrix to the events before tagging to estimate the mistag and QCD backgrounds and also use the pretag sample in the W +heavy-flavor background determination assuming no $t\bar{t}$ content. A summary of the number of observed events and the background predictions, both before and after the correction, as a function of the number of jets is given in Tab. XV. It is worth noting the excellent agreement between the expected and observed tagged events in the W +1 and 2 jet samples, where the expectation is dominated by the mistag contribution, and the $t\bar{t}$ contribution is negligible. This is a further validation of the mistag matrix.

The cross section is calculated as

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{A_{t\bar{t}} \cdot \epsilon_{t\bar{t}} \cdot \int L dt}, \quad (13)$$

where N_{obs} is the number of events with ≥ 3 jets in which at least one jet has an SLT μ tag, N_{bkg} is the corrected background, $A_{t\bar{t}}$ and $\epsilon_{t\bar{t}}$ are the $t\bar{t}$ event acceptance and tagging efficiency, and $\int L dt$ is the integrated luminosity. The acceptance and efficiency are discussed in Section V, and summarized for the signal region in Tab. XVI. We measure a total $t\bar{t}$ cross section of

$$\sigma(p\bar{p} \rightarrow t\bar{t}X) = 9.1 \pm 1.1_{-0.9}^{+1.0} \pm 0.6 \text{ pb}, \quad (14)$$

where the first uncertainty is statistical, the second is systematic, and the third is from the luminosity. This cross section value uses acceptances and tagging efficiencies appropriate for a top mass of 175 GeV/ c^2 . The acceptances and efficiencies, and therefore the calculated cross section, change slightly for other assumed top masses. The calculated cross section is 3% higher assuming a top mass of 170 GeV/ c^2 , and 4% lower assuming a top mass of 180 GeV/ c^2 . As a check we also measure the cross section separately for events in which the primary lepton is an electron and in which it is a muon. We measure 9.5 ± 1.2 pb when the primary lepton is an electron and 8.5 ± 1.2 pb when it is a muon. The uncertainties in both cases are statistical only.

Figure 11 shows, in bins of the number of jets in W +jets candidates, the expected number of tagged background and $t\bar{t}$ (normalized to the measured cross section) events together with

the number of observed SLT μ tags.

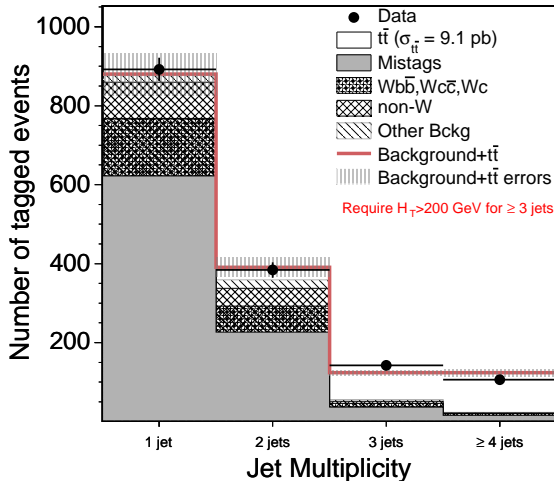


FIG. 11: The expected background and observed tags in $W+1, 2, 3$, and 4-or-more jets events. The expected $t\bar{t}$ contribution is normalized to the measured cross section.

In Fig. 12 through 14 we examine a few kinematic features of the tagged events. In each case the data are compared to the expected backgrounds plus $t\bar{t}$, normalized to the measured cross section. The agreement between data and expectation is good. The only slight exceptions are a few bins at low E_T in the $W+ \geq 3$ jet events in Fig. 12, where the number of observed tags exceeds somewhat the expectation. This is consistent with the excess seen in the low E_T jet data in Tab. XIII, which is folded into the systematic uncertainty on the measurement.

X. CONCLUSIONS

Using 2 fb^{-1} of integrated luminosity collected by the CDF II detector, we have measured the total cross section for $t\bar{t}$ production in $p\bar{p}$ collisions with a center-of-mass energy, $\sqrt{s} = 1.96 \text{ TeV}$. The measurement begins by selecting a dataset of W +jets candidates. We separate signal from background by identifying candidate semileptonic decays of b -hadrons into muons. This technique was first published in Reference [4]. This measurement is an update that uses ten times the amount of data of the previous measurement and a new technique for evaluating the dominant background (see Section VI) of misidentifying a jet

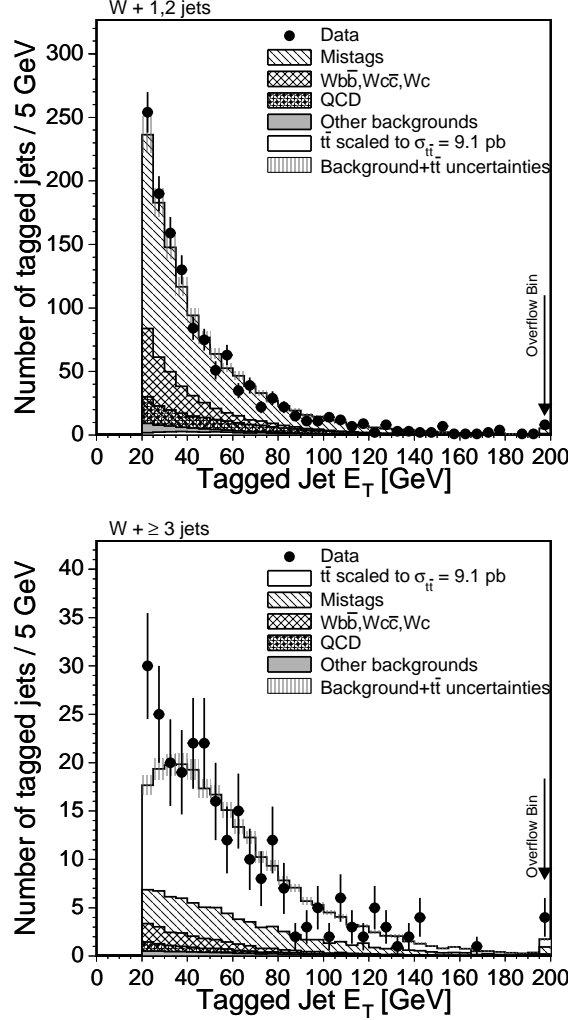


FIG. 12: Comparison of the jet E_T distributions for tagged jets and for expectations from mistags, W +heavy-flavor, QCD and $t\bar{t}$ events. The upper plot is for W +1- and 2-jet events and the lower plot for W +3-or-more-jets events.

from a light-flavor quark as one containing a b -hadron. The measured $t\bar{t}$ cross section is

$$\sigma(p\bar{p} \rightarrow t\bar{t}X) = 9.1 \pm 1.1^{+1.0}_{-0.9} \pm 0.6 \text{ pb}, \quad (15)$$

consistent with the expectation of $6.7^{+0.7}_{-0.9}$ pb for standard model production and decay of top quark pairs with a mass of $175 \text{ GeV}/c^2$. The measurement agrees well with other CDF measurements of the $t\bar{t}$ production cross section [23]. Assuming the cross section increases 0.2 pb for every $1 \text{ GeV}/c^2$ decrease in the top mass, then at the world average top mass of $172.4 \text{ GeV}/c^2$ the theoretical cross section is approximately 7.2 pb. Using a linear fit to the

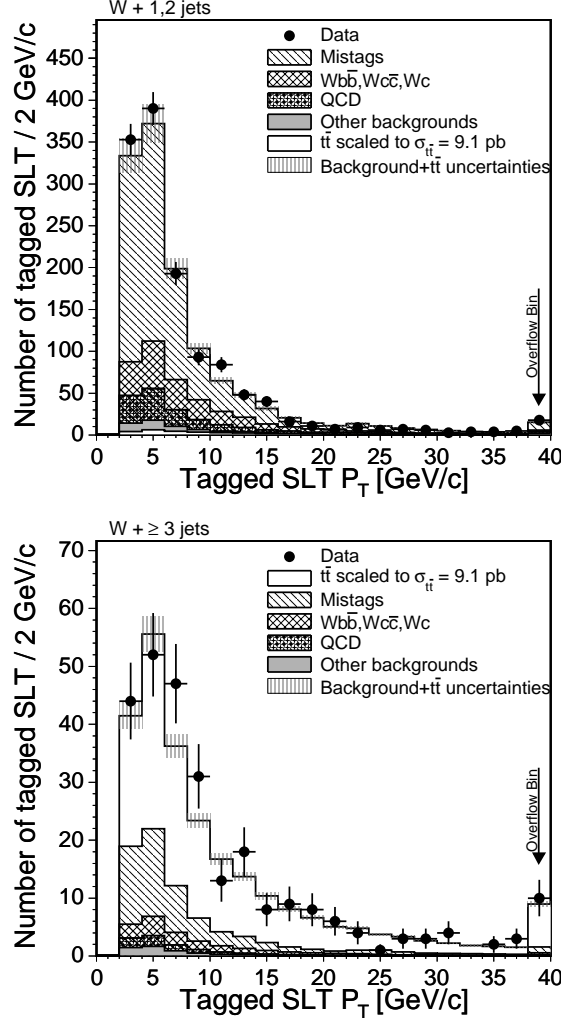


FIG. 13: P_T of the SLT μ tags compared with expectations from backgrounds and $t\bar{t}$. The upper plot is for $W+1$ - and 2-jet events and the lower plot for $W+\geq 3$ -jet events.

mass dependence, the measured cross section was estimated at the world average top mass and is found to be 8.9 ± 1.6 pb. The kinematic distributions of the tagged sample are also consistent with standard model expectations. The observed number of tags in $W+1$ - and 2-jet events is in excellent agreement with expectations from background, indicating that the backgrounds are well understood.

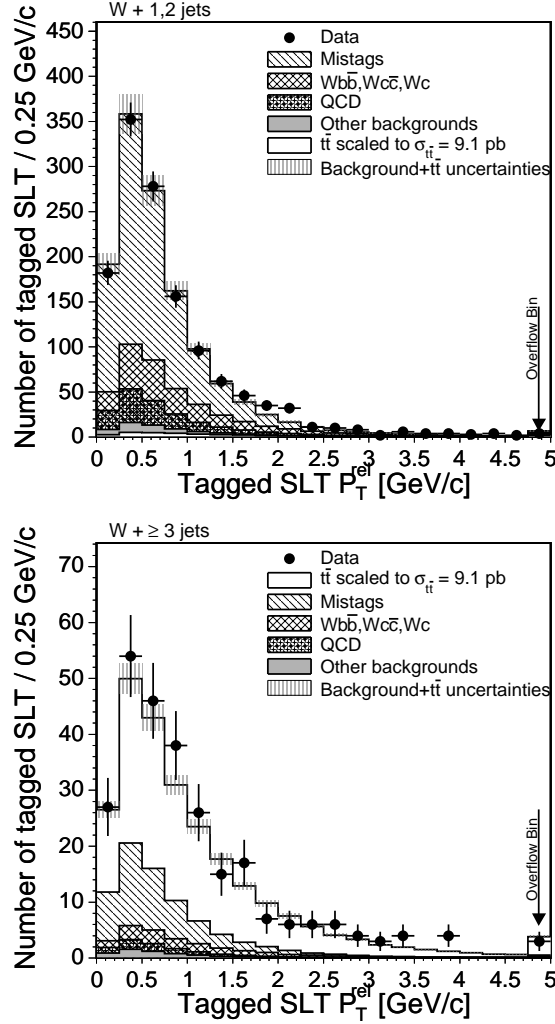


FIG. 14: The distribution of P_T relative to the jet axis (P_T^{rel}) for tags in data, compared with expectations from backgrounds plus $t\bar{t}$. The upper plot is for 1- and 2-jet events and the lower plot for ≥ 3 -jet events.

XI. ACKNOWLEDGEMENTS

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bun-

desministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

-
- [1] M. Cacciari *et al.*, J. High Energy Phys. 0809, 127 (2008); N. Kidonakis and R. Vogt, Phys. Rev. D **78** 074005 (2008); S. Moch and P. Uwer, Nucl. Phys. Proc. Suppl. **183** 75, (2008).
 - [2] We use a (z, ϕ, θ) coordinate system where the z -axis is in the direction of the proton beam, and ϕ and θ are the azimuthal and polar angles respectively. The pseudo-rapidity, η , is defined as $-\ln(\tan \frac{\theta}{2})$. The transverse momentum of a charged particle is $P_T = P \sin \theta$, where P represents the measured momentum of the charged-particle track. The analogous quantity using calorimeter energies, defined as $E_T = E \sin \theta$ is called transverse energy. The missing transverse energy is defined as $\cancel{E}_T = - | \sum_i E_T^i \hat{n}_i |$ where E_T^i is the magnitude of the transverse energy contained in each calorimeter tower i in the pseudo-rapidity region $|\eta| < 3.6$ and \hat{n}_i is the direction unit vector of the tower in the plane transverse to the beam direction.
 - [3] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 082004 (2006); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).
 - [4] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 032002 (2005)
 - [5] Ulysses Allen Grundler, “A Measurement of the $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using Soft Muon Tagging”, Ph.D Thesis, University of Illinois at Urbana-Champaign, 2008. FERMILAB-THESIS-2008-27.
 - [6] The CDF II Detector Technical Design Report, Fermilab-Pub-96/390-E; D. Acosta *et al.*, Phys. Rev. D **71**, 052003 (2005).
 - [7] S. Klimenko, J. Konigsberg and T.M. Liss, Fermilab-FN-0741.
 - [8] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
 - [9] G. Corcella *et al.*, J. High Energy Phys. 01, 10 (2001).
 - [10] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).

- [11] D. J. Lange *et al.*, Nucl. Instrum. and Methods Phys. Res., Sect. A **462**, 152, (2001).
 - [12] Daniel Sherman, “Measurement of the Top Quark Pair Production Cross Section with 1.12 fb-1 of pp Collisions at $\sqrt{s} = 1.96$ TeV”, Ph.D. Thesis, Harvard University.
 - [13] M. Mangano *et al.*, J. High Energy Phys. 7, 1, (2003).
 - [14] F. Maltoni and T. Stelzer, J. High Energy Phys. 02, 27 (2003).
 - [15] E. Gerchtein and M. Paulini, ECONF **C0303241**, TUMT005 (2003), arXiv:physics/0306031.
 - [16] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **91**, 241804 (2003); A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 031109 (2006).
 - [17] A. Abulencia *et al.* (CDF Collaboration), arXiv:hep-ex/0609021v1 submitted to Phys. Rev. Lett.
 - [18] A. Bhatti *et al.*, Nucl. Instrum. and Methods Phys. Res., Sect. A **566**, 375 (2006).
 - [19] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
- The ZZ cross section of 3.4 pb is appropriate for the PYTHIA Monte Carlo sample we use that includes events with one off-shell Z. The value is arrived at by normalizing the PYTHIA sample to the Campbell and Ellis cross section of 1.58 pb for two on-shell Z bosons.
- [20] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).
 - [21] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
 - [22] A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C **4** 463 (1998).
 - [23] The CDF Collaboration, CDF Conference note 9448 (2008);
<http://www-cdf.fnal.gov/physics/new/top/confNotes/>

	1 jet	2 jet	3 jets	≥ 4 jets	≥ 3 jets
<i>WW</i>					
σ_{theory}	12.4 \pm 1.2 pb				
A (%)	2.44 \pm 0.01	2.62 \pm 0.01	0.403 \pm 0.004	0.121 \pm 0.002	0.524 \pm 0.005
ϵ (%)	0.49 \pm 0.03	0.76 \pm 0.04	0.88 \pm 0.09	1.56 \pm 0.23	1.06 \pm 0.09
N_{WW}	2.986 \pm 0.299	5.001 \pm 0.394	0.892 \pm 0.190	0.475 \pm 0.118	1.395 \pm 0.228
<i>WZ</i>					
σ_{theory}	3.96 \pm 0.40 pb				
A (%)	1.085 \pm 0.007	1.317 \pm 0.007	0.233 \pm 0.003	0.070 \pm 0.002	0.302 \pm 0.004
ϵ (%)	0.85 \pm 0.06	1.72 \pm 0.07	1.46 \pm 0.16	2.69 \pm 0.39	1.77 \pm 0.15
N_{WZ}	0.740 \pm 0.075	1.821 \pm 0.128	0.274 \pm 0.044	0.151 \pm 0.036	0.432 \pm 0.058
<i>ZZ</i>					
σ_{theory}	3.4 \pm 0.3 pb				
A (%)	0.104 \pm 0.002	0.097 \pm 0.002	0.060 \pm 0.001	0.012 \pm 0.001	0.042 \pm 0.001
ϵ (%)	1.0 \pm 0.2	2.4 \pm 0.3	2.3 \pm 0.5	1.6 \pm 0.5	2.1 \pm 0.4
N_{ZZ}	0.07 \pm 0.02	0.16 \pm 0.05	0.05 \pm 0.02	0.013 \pm 0.006	0.06 \pm 0.02
<i>Drell – Yan $\rightarrow \tau\tau$</i>					
σ_{theory}	333 \pm 4.2 pb				
A (%)	0.112 \pm 0.001	0.054 \pm 0.001	0.0058 \pm 0.0004	0.0014 \pm 0.0002	0.0073 \pm 0.0004
ϵ (%)	0.4 \pm 0.1	0.4 \pm 0.1	1.6 \pm 0.7	1.3 \pm 0.5	1.3 \pm 0.5
$N_{\text{Drell–Yan} \rightarrow \tau\tau}$	2.65 \pm 0.57	1.54 \pm 0.43	0.65 \pm 0.28	0.13 \pm 0.05	0.65 \pm 0.27
<i>s-channel Single Top</i>					
σ_{theory}	0.88 \pm 0.11 pb				
A (%)	1.12 \pm 0.01	2.66 \pm 0.01	0.717 \pm 0.005	0.203 \pm 0.003	0.920 \pm 0.006
ϵ (%)	5.0 \pm 0.1	9.7 \pm 0.1	10.2 \pm 0.2	11.1 \pm 0.4	10.4 \pm 0.2
$N_{s\text{–chan}}$	1.00 \pm 0.11	4.61 \pm 0.46	1.31 \pm 0.15	0.40 \pm 0.05	1.71 \pm 0.19
<i>t-channel Single Top</i>					
σ_{theory}	1.98 \pm 0.08 pb				
A (%)	1.91 \pm 0.01	2.10 \pm 0.01	0.345 \pm 0.003	0.057 \pm 0.001	0.402 \pm 0.004
ϵ (%)	4.38 \pm 0.09	5.19 \pm 0.09	5.96 \pm 0.24	7.37 \pm 0.64	6.16 \pm 0.22
$N_{t\text{–chan}}$	3.36 \pm 0.37	4.39 \pm 0.47	0.83 \pm 0.11	0.17 \pm 0.03	1.00 \pm 0.13

50
 TABLE XII: Summary of Monte Carlo derived backgrounds. The theoretical cross sections [19] [20] [21] are inclusive. The acceptance, A , includes the branching fraction to events

Jet $E_T^{corr.}$ [GeV]	Observed	Predicted	Δ [%]
20-30	1892	1641 ± 29	-15.3 ± 3.3
30-45	1561	1693 ± 45	7.8 ± 3.4
45-65	701	768 ± 46	8.7 ± 6.4
65-90	464	462 ± 46	-0.5 ± 11.0
≥ 90	466	466 ± 76	-0.1 ± 16.9
≥ 20	5084	5029 ± 219	-1.1 ± 4.6

TABLE XIII: Checks of the mistag matrix in different jet E_T bins. $\Delta = (\text{Pred.} - \text{Obs.}) / \text{Pred.}$. These values of Δ are weighted using the $W + 3\text{-or-more jets}$ distribution to determine a systematic uncertainty on the mistag prediction.

Source	Fractional Sys. Uncert. (%)	$\Delta\sigma_{t\bar{t}}$ (%)
Acceptance Modeling and SLT Tagging Efficiency	7.7	+8.3 -7.5
Mistag Matrix Prediction	5	3.6
$Wb\bar{b} + Wc\bar{c} + Wc$ Prediction	38	5.3
QCD Prediction	19 (e) 124 (μ)	1.1
Drell-Yan and other MC backgrounds	11	0.4
Total Systematic Uncertainty		+10.5 -10.0

TABLE XIV: Summary of systematic uncertainties.

	$H_T \geq 0$ GeV		$H_T \geq 200$ GeV		
Background	1 jet	2 jet	3 jets	≥ 4 jets	≥ 3 jets
Taggable events	75595	18264	2587	1120	3707
Mistags	622 \pm 31	226 \pm 12	53.0 \pm 2.7	31.4 \pm 1.6	84.5 \pm 4.3
$Wb\bar{b}+Wc\bar{c}+Wc$	145 \pm 55	66.6 \pm 25.2	15.3 \pm 5.8	8.5 \pm 3.2	23.0 \pm 8.7
QCD multijet	91.9 \pm 16.5	44.9 \pm 10.4	7.0 \pm 1.5	4.1 \pm 0.9	11.1 \pm 2.4
$WW+WZ+ZZ$	3.80 \pm 0.44	6.98 \pm 0.66	1.21 \pm 0.23	0.64 \pm 0.14	1.88 \pm 0.30
Drell-Yan $\rightarrow \tau^+\tau^-$	2.65 \pm 0.57	1.54 \pm 0.43	0.65 \pm 0.28	0.13 \pm 0.05	0.65 \pm 0.27
Drell-Yan $\rightarrow \mu^+\mu^-$	6.02 \pm 1.25	4.12 \pm 0.88	0.82 \pm 0.44	0.00 \pm 0.19	0.82 \pm 0.48
Single top	4.36 \pm 0.39	9.00 \pm 0.66	2.14 \pm 0.18	0.57 \pm 0.06	2.71 \pm 0.23
Total Background	876.5 \pm 53.6	359.0 \pm 24.0	80.2 \pm 5.4	45.3 \pm 3.0	124.6 \pm 8.2
Corrected Background	–	–	79.5 \pm 5.3		79.5 \pm 5.3
$t\bar{t}$ Expectation ($\sigma=6.70$)	2.60 \pm 0.33	23.5 \pm 1.8	50.1 \pm 3.6	74.2 \pm 6.5	124.3 \pm 9.1
Total Background + $t\bar{t}$	879.1 \pm 53.6	382.5 \pm 24.1	203.9 \pm 10.6		203.9 \pm 10.6
Tagged events	892	384	142	106	248

TABLE XV: Number of tagged events and the background summary. The uncertainty on the total background is not a simple sum in quadrature of the individual backgrounds because of the correlation between the mistag, W +heavy-flavor, and QCD background predictions.

	Electrons	CMUP Muons	CMX Muons
Acc. no Tag (%)	$3.71 \pm 0.01 \pm 0.21$	$2.05 \pm 0.01 \pm 0.14$	$0.946 \pm 0.004 \pm 0.050$
Event Tagging Eff. (%)	$14.02 \pm 0.08 \pm 0.72$	$13.07 \pm 0.10 \pm 0.67$	$13.38 \pm 0.16 \pm 0.68$
Acc. with Tag (%)	$0.520 \pm 0.003 \pm 0.039$	$0.268 \pm 0.002 \pm 0.022$	$0.127 \pm 0.002 \pm 0.009$
Luminosity (pb ⁻¹)	2033.6 ± 119.6	2033.6 ± 119.6	1992.5 ± 117.2
Denominator (pb ⁻¹)	$10.58 \pm 0.07 \pm 0.80 \pm 0.62$	$7.97 \pm 0.06 \pm 0.49 \pm 0.47$	
Total denominator (pb ⁻¹)	$18.56 \pm 0.09(\text{stat.})\pm 0.94(\text{sys.})\pm 1.09(\text{lum.})$		

TABLE XVI: Summary of components of the denominator for the cross section calculation. The $t\bar{t}$ acceptance and tagging efficiency for 3-or-more-jets events is determined using PYTHIA Monte Carlo.